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LA JOLLA, CALIFORNIA
March, 1942

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Contribution No. 100

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anford and San Francisco July 24 to August 12, 1939.)

INDICATOR VALUES OF PHYTOPLANKTON

By W. E. Allen

T IS generally understood that all kinds (or any kinds) of land-dwelling or-
anisms have more or less value as indicators of habitat relationships, of popu-
tion trends, and of other environmental or biological conditions, local or
gional. It has not been so generally understood, or recognized, that water-
welling organisms have similar values as indicators. Still, it is well known
at in the nearly sixty years since the time of Hensen's attempts to use plank-
n populations for estimating fertility, or productivity, of the sea, increasing
umbers of investigators have undertaken to use marine life in numerous
ays for "indicator" purposes.

At the Scripps Institution of Oceanography, researches on marine phyto-
lankton were initiated in 1917 for the primary purpose of assembling data
indicate conditions, and changes of conditions, of fertility of California
as. At that time it was assumed that marine life resembled land life in being
ependent on the abundance and activities of photosynthetic organisms (or-
inarily roughly grouped together as "green plants"). It was assumed also
at the microscopic "green plants" afloat in the sea contributed most to sup-
ort of marine populations of animals, among which commercial fishes were
ost conspicuous. Preliminary studies in southern California, as well as re-
lts of North Sea and other investigations, led to the additional assumption
at marine diatoms and dinoflagellates were the groups most favorable for
servation while being at the same time fairly representative in respect to
hotosynthetic activities.

Because of war-time interest in marine sources of human food, the first
udies of phytoplankton at the Scripps Institution were designed particu-
rly for getting information indicative of abundance of "ocean pasturage"
that region. While the work of the summers of 1917 and 1918 may seem
bsurdly inadequate and inconsequential in the light of our knowledge of
day, it did show that phytoplankton was not distributed uniformly through
e water, that its abundance was not constant in any locality at any level,
d that proportional representation of species was continually changing in
l populations. In other words, it became evident that "indicator values" of
lankton diatoms or any other organisms were obscured by the intricacy of
lationships, and the kaleidoscopic changes of relationships, to such a degree
at they could not be applied immediately and directly to the problems of
stenance of commercial fishes.

However, the original assumption that changes in abundances of diatoms
d dinoflagellates were closely related to changes in general productivity of
e sea was not abandoned. Instead of stressing the idea of using phytoplank-
n populations as indicators of presence or absence of marketable fish within
given area, it was decided to use them as indicators of regional trends of fer-
lity, or productivity, over periods of years, or even decades. Consequent to
is decision the Institution established a series of daily collections of phyto-
lankton at its pier in 1919, supplemented by such series in other localities a
ttle later. These series have shown a high value of phytoplankton populations
r use as indicators of relative fertility of different localities and regions in
ifferent seasons and years. For example, La Jolla Bay showed more produc-
on than Point Hueneme (near Oxnard, California, more than 100 miles dis-
nt northerly) for the first three years (less thereafter), while showing a
irly close resemblance to Oceanside (25 miles away) through five years. Over
period of five years, daily catches at the Farallone Islands (outside of San

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Institution of Oceanography
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Francisco Bay) showed very thin populations only, indicating low fertilit of the sea near the islands. Another daily series at Scotch Cap in the Aleutia Islands showed intermediate production of diatoms and dinoflagellates. Thu by use of phytoplankton populations as indicators, we get the idea of extren differences between regions in respect to productivity.

For the benefit of those not familiar with the vagaries of distribution oceanic populations of all kinds, perhaps it should be noted that heavy pr duction of "pasturage" at a particular time or place, or over a considerab period, does not mean, necessarily, that commercial fishes or other anim populations must be abundant also there and then. For one thing, great de sity of phytoplankton is well known to be distasteful or detrimental to anim populations. Also, plant production may be heavy at a time when few anima are in a condition to use it. Furthermore, the phytoplankton may be consume mainly in a locality less favorable for its growth after drifting away from locality highly favorable for its production. That is to say, locality recor may indicate good fertility in respect to one type of organisms and not f others. For such reasons it appears certain that while marine diatoms ar dinoflagellates may reach abundances indicating good fertility of the sea a particular locality, it cannot be assumed that they indicate reliably the d gree of productivity of animal populations. That value may appear in tl future, but it is not available from present knowledge.

The indicator values of large abundances of phytoplankton in respect movements of water masses are much more satisfactory, as exhibited by diffe ent series of collections obtained by the Scripps Institution in a period twenty-two years. Even the less satisfactory series of 1917 and 1918 showe larger catches of phytoplankton to be related to "upwelling." Doubtless "u welling" may occur without being accompanied by increase in abundance plants, but in certain localities large abundance of "ocean pasturage" de nitely does indicate "upwelling." Later investigations by the Scripps Instit tion, especially in the cruises of 1938 off the coast of southern California, ha shown also that good or large abundances of marine diatoms are good indic tors of the paths of flow of major currents moving more or less nearly parall with the coast and of certain eddies or circuits developed by them.

To agriculturists it is well known that land plants of many kinds are goo indicators of soil conditions, not only in respect to productiveness, but also respect to chemical composition or physical constitution. In some instanc abundance is the main feature of indicator usefulness. In other instances tl characteristics of form and development of individual plants are more ir portant. Acid soils, alkali soils, wet soils, dry soils, and various types ar combinations of types may support more or less vegetation tolerant of the peculiarities. An experienced man driving rapidly along a highway can us ally make a close guess at the characters of the soils within his view, mere by use of plant indicators.

For at least one very good reason the floating plants of the sea have nev reached so high a degree of indicator value: their microscopic size has pr vented observations and comparisons requisite for dependable understandi of relationships. In addition, it should be noted that constituents of the se water substratum are not so stable in respect to either kinds or quantities are the constituents of most land substrata. Nevertheless, it appears th there is opportunity for considerable usefulness of phytoplankton indicato of conditions of the sea-water substratum. Doubtless this is easiest to see those species of diatoms which are known to thrive best on the high seas, or coastal waters, or in estuaries, or in brackish waters, or in high latitudes, n low latitudes. But it may be equally important if certain species show arked changes in abundance or in conformation according to changes in alinity, temperature, or abundance of particular chemical constituents. As ur knowledge of the composition of sea-water and its changes or variations ecomes more accurate, such indicator values of plankton diatoms and other icroscopic plants should increase greatly. Indeed, for certain investigations hey may reach prime importance by attracting attention to the fact that a iven sample of "sea water" has peculiar properties or that it contains some ubstance which affects the plants although it may go unnoticed in the routine f direct chemical examinations. Of more practical application is the use of a eries of phytoplankton samples running parallel with a series of chemical amples to verify or substantiate the chemical observations. In the Institution ruises of 1938 it happened at one time that Station 9 showed some chemical onditions different from those expected and that some doubt arose concerning he validity of the chemical work for that station. Comparison with the diatom ecords for that station revealed differences of similar magnitude in numbers f diatoms and authenticated the chemical work. This experience not only resents new convincing evidence that phytoplankton has indicator values orth developing and exploiting, but it also shows the high importance of lose coöperation and coördination between all kinds of oceanic investigation.

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METHODS OF FIELD AND LABORATORY PROCEDURE IN PHYTOPLANKTON RESEARCH AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY OF THE UNIVERSITY OF CALIFORNIA

By W. E. Allen

When I first became associated with the Scripps Institution at La Jolla in 1917 there was no record of species of diatoms living in southern California waters, and there were only the vaguest of surmises concerning total annual production of plankton diatoms, seasonal changes in abundance, geographical differences in occurrence, bathymetrical differences in occurrence, relationships to chemical constituents of sea water, and relationships to physical conditions of sea water including the fundamentally important relationship to movements of water masses, both local and general. Concerning dinoflagellates the situation was much better, thanks to the active interest of Professor C. A. Kofoid, although there was not much reliable information available except in the fields of taxonomy and morphology.

Field work.—Faced with these conditions and strongly impressed by unsatisfactory experience with tow nets as collecting equipment in fresh water, I began immediately to seek for methods by which material could be gathered rapidly, but reliably, at low cost and under widely differing circumstances. By the time that I began permanent residence at the Institution in 1919 I had experimented more or less with all methods of collecting phytoplankton known at that time. As a result I became convinced that filtration of a measured volume of water through No. 25 silk bolting cloth would give the most satisfactory results for plankton diatoms and armored dinoflagellates, the forms already selected as most suitable for long-term researches on marine phytoplankton.

First trials of the measured water method of filtration (as distinguished from centrifuging or settling) were made with a tow net of No. 25 silk (average diameter of openings about .05 millimeter in new material) which was then in use for surface collecting alongside the Institution pier. In these trials a sample was taken by towing over a measured distance calculated to pass 439 liters of water through the meshes. To allow for possible clogging, irregular pull, and other errors of the tow this estimate was reduced to 200 liters for comparison. Immediately following the tow haul 100 liters of water was dipped from a point traversed in the tow and poured through the same net suspended from the pier rail. In 9 pairs of samples the catches by measured water exceeded those by tow in numbers per liter, the preponderance ranging from 12 times to 87 times. Not only was the collecting of measured volumes by filtration easier to control, but the results were far more reliable even in surface work beside the pier. It was seen at once that the adoption of this method would open the way for very great expansion of collecting at the surface level and that its accuracy in operation at subsurface levels might be as important as the accuracy of its results in gathering material from the point of sampling. An officer of the Pacific Coast Steamship Company confirmed part of this expectation almost immediately by obtaining a series of surface catches between San Diego and Seattle, the 3-gallon samples of water to be filtered being dipped from the sea and filtered through a short net while the ship was going at full speed. A little later, members of the scientific staff of the Scripps Institution tested the method for collecting at lower levels, using the Kofoid closing bottle (5 gallons capacity) for getting water from specific levels.

Since 1919 the Institution has accumulated more than 7000 catches of

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phytoplankton by use of this filtering method, of which about 2000 catches have been obtained at levels below the surface, mostly by aid of the Allen closing bottle (5 liters capacity). Probably not more than one-fifth of that number would have been obtained by any other method. A number of series were obtained from waters of the East Pacific from Peru to the Aleutian Islands and one series even extended as far as Australia. After ten years of use of the method of filtering at the Scripps Institution pier, it was decided to try a settling method in order to capture organisms too small to be retained by No. 25 silk.

Since 1930, daily catches at the pier have been made by dipping a liter of water from the surface alongside (500 milliliters at two different points) and leaving it in a tall glass cylinder after adding a killing fluid. After twenty-four hours the excess fluid is decanted to about 100 milliliters and left in a smaller cylinder from which the excess is again decanted at the next collecting time to leave about 50 milliliters in a small cylinder from which the excess is finally taken by pipette. The remainder is stored in a small vial. Ten years of experience with this method leads to the opinion that it is satisfactory for the diatoms and armored dinoflagellates, while also capturing most of the nannoplankton reasonably well. Because of its convenience and general effectiveness there this method is being continued in use at the Scripps Institution pier. For routine collecting of nannoplankton the settling method appears to be just as good as the centrifuge method preferred by many investigators and it requires much less expense, care, and effort. Both are subject to variable error when handling organisms which are strongly agglutivative, cohesive, or adhesive, but with proper use both may be superior to any kind of filtering method which requires repeated use of the same filtering material because they avoid clogging and spreading of fibers which affect old filtering surfaces. This is especially true when sampling thin populations. However, the use of a conical net for filtering reduces the aging error of mill silk because new filtering surface automatically comes into service as the meshes are clogged in the lower parts of the net. A used net in good condition actually collects plankton diatoms better than a new one when used for filtering, although it would become rapidly worse if used for towing. For practical operation at sea the filtering method is still considered superior to any other for diatoms and armored dinoflagellates.

Microscopic study.—In the course of twenty years, microscopic study of phytoplankton at the Scripps Institution has covered about 26,000 catches. To anyone acquainted with material of this kind it is obvious that careful examination of specimens and rigid identification of component species is not possible with such speed of examination. Still, it is probable that one-fourth of my time and that of my assistants and associates has been devoted to study of specimens in detail. One finds it highly satisfying to deal with material which can be reliably named. Furthermore, it is irritating to be obliged to record forms of doubtful identity. Experiences of more than twenty years involving microscopic examination of hundreds of thousands of specimens has shown conclusively that many species cannot be distinguished unless proper recognition marks are present, that many species grade toward each other to a degree making the establishment of border lines impossible, that almost all species may differ more or less in conformation of individuals according to differences in conditions of development, and that many species must be examined from different angles not possible to obtain in a counting cell. The fact of the matter is that great numbers of individual specimens could never be positively identified even if exhaustive study could be given them and that posi-

ve identification of others would require days of careful study, study which
ould have to be repeated for each individual if full certainty should be
ught. This is especially true of the plankton diatoms which sometimes pre-
nt in a single catch a half-dozen species easily confused and which frequently
esent in a single catch more than one group of two or three species easily
nfused. For such reasons the handling of the problem of identifications be-
mes a feature of method in microscopic study. Except for occasional reviews
the literature and of representative specimens in our mounted collections, I
longer attempt to make exact identification of refractory specimens. If they
e not recognizable under the conditions of quantitative study, I record speci-
ens under a catch-all designation, or I apply a species name which expresses
probable relationship at the same time that it serves to separate forms which
ter study may make identifiable or deserving of special scrutiny.

For routine study under the microscope the volume of the catch is usually
duced to 10 milliliters or 100 milliliters from which 1 milliliter is taken to
l a Sedgwick-Rafter slide, in which it is examined under a magnification of
ty to one hundred diameters. Some correspondence of the last two years has
own that investigators in out of the way places may have trouble in getting
at equipment. For that reason it may be worth while to suggest that a tem-
rary S-R slide can be made by building a rectangle on an ordinary micro-
ope slide with paraffine or other wax, or by cementing a rectangle of card-
ard of suitable thickness to such a slide with paraffine. The essential thing is
have a waterproof enclosure 1 millimeter deep, 20 millimeters wide, and 50
illimeters long (inside dimensions). For permanent use our University
achinists have made for me several frames of brass having these inside di-
ensions, most of which I have cemented to ordinary glass slides with thin
ms of paraffine, others with commercial cement. If cover glasses to fit are
rd to get in some localities, sheets of mica may be serviceable. At any rate, a
tle inventiveness may serve to meet the need.

Having mounted a 1-millimeter sample of the catch in a S-R slide I usually
unt the smallest fraction of the slide that appears likely to give a fair basis
r computing the numbers in the catch. The standard fraction for a thin catch
one-tenth of the slide. With the lens combination I am using now this is a
ttle more than one round trip from end to end through the middle of the
ide. For heavy catches I often stop with one-twentieth of the slide. Single
ecies found in high abundance are often cut off at less. My view is that it is
tter to get records of *many* catches which are good approximations than to
rive excruciatingly for an accuracy of enumeration and calculation which
ay be far out of proportion in comparison with the unavoidable errors of
mpling in the *few* catches which can be covered under excessive attention
numerical probabilities.

In harmony with this same reasoning I have tried to reduce the time and
bor in handling certain series by two different methods. First, at the Insti-
tion pier, when populations are running very thin over periods of a week
more, I take a sample from each daily catch for a seven-day period and
mbine them to obtain an average sample for that time. Enumeration of
ecimens is then carried through as it might have been for any single catch,
d from the numbers recorded the average representation for the seven-day
riod is calculated. When catches are heavy or when certain days are in-
uded in a "plankton pulse" the catch for each day is studied separately in
der to obtain details for comparison with records of chemical and physical
nditions, but the counts for each seven-day period are averaged. Because
r pier records have become so voluminous in the course of twenty years of

operation, our standard tabulations include only these averages of weeks (obtained by either procedure), but day-by-day tabulations are also made a times for special purposes. Second, offshore catches of extreme thinness ar examined by taking a sample drop from the bottom of the container (withou stirring or shaking) and placing it on an ordinary glass slide for the purpos of recording the presence of the few specimens observable. No attempt is mad at calculation and the numbers yielded by that catch are simply recorded a negligible. In this connection the term "negligible" is purely quantitative i meaning. The species record covers any qualitative significance. Sometime thin catches are misjudged and the count is made with the regular S-R equipment. In that case, numbers varying according to circumstances from 100 t 500 per liter are rated as negligible. For some series the saving in microscop and clerical work by these two devices has been more than half. It is safe t say that they have made it possible to bring the routine work on 26,000 catche so nearly up to date with very few laboratory workers. As it is, every important series has been brought to 1939 or into 1939 both in respect to microscopi study and preliminary statistical treatment.

Contribution No. 102

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SUMMARY OF RESULTS OF TWENTY YEARS OF RESEARCHES ON MARINE PHYTOPLANKTON

By W. E. Allen

SUPPOSE that not the least important of the results of twenty years of work f any kind is its demonstration of merit for the methods and equipment used. t any rate, a number of visitors and correspondents have indicated their nderstanding that the measured water method of collecting, involving the se of the Allen Closing Bottle for subsurface sampling, and the short silk et for filtering, has been fundamental in the success of quantitative phases f phytoplankton investigations at the Scripps Institution of Oceanography.

Although quantitative studies on marine diatoms and dinoflagellates have een given primary attention in all the major researches on phytoplankton t the Institution in a period of more than twenty years, the desirability and ecessity for a good taxonomic foundation for these researches has been recogized throughout. It is true that in the preparatory studies of 1917 and 1918 ost of the time had been devoted to determining the identity of species benging to these groups in the southern California region, but it is also true at vexing problems of identification continued to exist or to arise after iniation of the permanent program in 1919. As a result of these conditions conderable improvement in classification has continued through the twenty-year eriod, culminating in 1939 in a monograph covering marine plankton diatoms f the East Pacific, contributed by Dr. E. E. Cupp. In this work she includes 60 species representing 51 genera, numbers fairly suggestive of the taxoomic characteristics of the population. Out of this number only about 30 pecies have ever reached numerical prominence in Institution collections. ess is known about the species of dinoflagellates, but only about 10 forms ave ever been excessively prominent. Still, two or three of them have been esponsible for the most striking discoloration ("red water") ever produced y phytoplankton in the sea water near the Scripps Institution.

Something has been learned concerning the ranges of occurrence although o careful examination has been made of the records for that purpose. For xample, our collections have not shown large numbers of armored dinoflageltes north of Monterey although it is possible that the densest populations f diatoms occur in latitudes far higher than that. Certainly the largest of ny in Scripps Institution collections were taken much farther north, notably f Gray's Harbor, Washington. Probably individual species of the two groups how this difference in tendency even more strongly, but only enough atteno has been given to the matter to find that among diatoms the genus *Thalasosira* is more prominent in Alaskan waters than it is south of the Columbia iver, that *Cerataulina* and *Guinardia* are more prominent in collections from exican waters than from those north of San Diego, and that *Chaetoceros ebilis* Cl., *Nitzschia seriata* Cl., and *Skeletonema costatum* (Grev.) are likely reach great prominence in any latitude.

Dinoflagellates have never been found in large numbers more than twenty iles from shore, although Institution records include several notations of rge numbers of diatoms found at various levels from the surface to fifty eters' depth at stations fifty miles from shore, or more. Without careful atention to the matter, it appears that a few species, especially the diatoms *haetoceros concavicornis* Mangin and *C. atlanticus* (Schütt), are more likely be found offshore than alongshore. Certainly the greatest numbers of both ese species have been found in offshore catches. Doubtless careful examinaon of the records for that purpose would show similar differences in some of

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the less prominent dinoflagellates as well as among other diatoms where the have escaped notice.

Chaetoceros concavicornis Mangin has been shown to be even more chara teristic of subsurface depths than it is of offshore waters, but no other specie of either diatoms or dinoflagellates has revealed so definite a tendency to liv below the surface. It is entirely possible that some species of both diatoms an dinoflagellates may be found to have this tendency if our records are scrut nized for that purpose; for example, the diatom *Eucampia zoodiacus* Ehr seems to do better below the surface although it is sometimes found in abun dance at or near it. However, the impression which I get from my long a quaintance with the material is that species doing well at the surface at on time or place may not be able to thrive there at another time or place. So als with respect to any particular depth down to fifty meters. Doubtless the re versals or oscillations of relative prominence of species at different levels ar sometimes dependent upon differences in tolerance of conditions found at par ticular levels at particular times and places. Almost all boat series which in clude subsurface catches show positively that largest abundance of diatom at stations in water more than fifty meters deep is likely to be at levels fro twenty to forty meters below the surface, sometimes one species and sometime another contributing most to the total. The species having greatest numbers a thirty meters is often different from the species having largest numbers in thinner population at the surface at the same station, but these ranks i prominence may be reversed at some other station. As yet we have not ha time to learn how far our records go toward affording solutions for these an a number of other problems of occurrence of phytoplankton at different levels

At the Scripps Institution pier, we have found at some time in the twent years at least a few representatives of almost every species of diatoms know to occur in the East Pacific. Furthermore, it has been surprising to me to fin that waters far from the open sea, like those of the Alexander Archipelago i Alaska and the Gulf of California in Mexico, appear to be just as likely t produce any designated species as is any other region. Certainly, most of th species prominent in the open sea in their latitudes are represented in colle tions from these relatively isolated regions. Therefore, it seems reasonable t say that no significant localization of species of phytoplankton is recognizabl in the East Pacific, even regional limitations of occurrence being unimpressive.

It is fairly certain that a number of species of both diatoms and dinoflagel lates have strong tendencies to appear only in one season of the year, but th relationship has not been worked out in detail for southern California sea After collecting was stopped at the Alaskan station at Scotch Cap in th Aleutian Islands in 1933, it was studied for a few of the leading species b Dr. Cupp. She found that few specimens of diatoms of any kind were to b taken in the winter months, *Biddulphia aurito* (Lyngb.) being the one ob served in most years. From April to August a considerable number of specie was represented in most of the five full years of collecting, several of the reaching their largest abundance of the year in that period. *Asterionella ja ponica* Cl. was one of those which reached maximum abundance after August

Perhaps I should not pass from this cursory survey of outstanding result of our imperfect study of relationships of species without referring to "re water," although we have given no intensive study to that phenomenon. A our collections of organisms from water contrastingly colored red (or a colo passing for red) show that the discoloration is caused mainly by superabun dance of one species, although accompanying species may themselves be fa

ore abundant than usual. In La Jolla Bay, with the single exception of 1938.
red water” has been caused by the small dinoflagellate *Prorocentrum micans*
hr. In that year the notorious genus *Gonyaulax* took precedence, *G. polyedra*
eing the species which reached excessive numbers, as it had not done in that
cality since 1916. North and south of San Francisco, *G. catenella* Whedon
as made its genus notorious by its responsibility for “mussel poisoning.” So
ar as I know, it has not been recorded from any locality except those along
e coast from Monterey Bay, California, to Coos Bay, Oregon. Now, in phyto-
lankton collections considerable distances from shore, I have just found it
identified by Whedon) in large abundance over a large area in the northern
hird of the Gulf of California and causing “red water” reported north of
ngel de la Guardia Island by Director H. U. Sverdrup of the Scripps Institu-
on on March 16, 1939, on the “Gulf Cruise” of the Institution research ship
. *W. Scripps*. In some casual collecting done by me alongshore on the coast
f Washington in 1938 I found “red water” consisting of almost pure cultures
f diatoms, *Aulacodiscus kittoni* Arn. (Copalis Beach) and *Asterionella kari-*
na Grun. (Long Beach). Doubtless “red water” presents the most vulnerable
oint for attack on some of the problems of species prominence and excesses
f abundance, perhaps those of whole diatom or dinoflagellate populations
lso, but as yet we have made no extensive and comprehensive effort to organ-
ze and conduct such an attack.

Because to us it seemed more important to have a good foundation in gen-
ral knowledge of populations and of the conditions under which populations
xist in the sea, our primary attention has been given to whole populations in
ll series of collections since the phytoplankton work was given full standing
s an Institution activity in 1919. Probably it will be best to discuss diatoms
nd dinoflagellates separately to avoid confusion.

Except for the Gulf of California series just mentioned, dinoflagellates
ever appeared to have much importance in catches taken offshore, even at
tations only five and ten miles from the Institution pier. Therefore it may
e supposed that whatever importance they have as components of popula-
ions of phytoplankton is narrowly restricted in southern California seas.
lowever, the trends of their occurrence, distribution, and numerical fluctua-
ions are well worth studying for whatever light they may throw on all kinds
f problems of fertility of the sea. Some of these trends are remarkably like
hose of plankton diatoms. Perhaps most important of our results is establish-
ent of the fact that the productive period for plankton dinoflagellates fluc-
uates around the twentieth week of the year, some years earlier and some
ears later, with the tendency to be early a little stronger at the La Jolla sta-
ion than it is at Point Hueneme, more than one hundred miles farther north.
ncreases (“pulses”) of abundance may occur at any time of year in southern
alifornia, but in most years they are longer and their production is higher
n the interval between the tenth and thirtieth weeks, mid-March to early
ugust.

I have been much interested in the very clear evidence that exceptionally
varm years are unfavorable for dinoflagellates. The years 1926 and 1931 were
uch years, and production was poor at both stations in both of them. Inas-
uch as 1926 is also on record as a year of shifting of fish populations to the
orth, it appears probable that this would have been a favorable year for ob-
erving the relationship between biological conditions and some of the recog-
izable chemical and physical conditions most closely allied with temperature.
ertain evidence not so clear suggests that there is a five-year (possibly also
ten- or twenty-year) periodicity in dinoflagellate productiveness, a five-year

period of inferior production including the very low year of 1926. Of cours we need the evidence of many more years before we can evaluate that sugge tion.

To those who may have thought of conditions in the ocean as being s nearly uniform that the routine of life must be rather monotonous, it ma seem somewhat shocking to know that our records show no two years alike i the twenty, no two months alike, and no two weeks alike. Continual change the order of nature as much in the sea as it is on land, weather and many othe influences playing their part in the eternal shifting of relationships. Wit nearly twenty years of daily observations behind me, I find it amusing whe I see an account of the work of some student of nature who has learned th normal routine of life in a larger or smaller space on sea or land by an intensive study conducted through a few weeks or months or even years, and on relatively small number of organisms.

Our records show that armored dinoflagellates may be extremely numerou at times, literally millions of them in each liter of water. On the other han it is shown just as clearly that they rarely appear in numbers greater tha tens of thousands per liter. Because of the rarity of their production in larg abundance, I have come to consider a thousand per liter as a fairly good showing for this group in ordinary catches, even alongshore. For that reason a abundance of millions per liter appears to me to be more significant than i is for the diatoms. That is to say that I think it possible that a dense swar of the one might be more favorable for intensive study than a like swarm o the other because of the contrasts in activity or in the kinds of response t certain influences in denser and thinner populations.

Over the twenty-year period diatoms show a strong tendency to be mos productive at about the same time as the dinoflagellates. However, a greate difference is discernible between the two stations at La Jolla and Point Hueneme, the fluctuation of productivity being around the fifteenth (or seventeenth) week at La Jolla and the twentieth (or twenty-second) week at Poin Hueneme. There is also more irregularity at both stations in the appearanc of highly productive pulses, one at La Jolla in January reaching over a hundred thousand cells per liter and several in tens of thousands occurring i winter months in the twenty years. In fact, February was the most productiv month at La Jolla in 1920, one of the best years for diatoms.

The warm-water years of 1926 and 1931 were unfavorable years for diatoms, although possibly a little less so than for dinoflagellates. At any rat there was more difference in the effects at the two stations, Point Huenem producing much larger numbers through more than half of each year an about the same for the remaining time.

The records for diatoms show even more clearly than those for dinoflagellates the risk of drawing wrong conclusions from too little evidence in natur For example, the weekly averages of daily catches for the first three years a La Jolla are mostly larger than those for corresponding weeks at Point Hueneme, and the year totals are larger. Surely one might be excused for concluding that La Jolla was the more productive station. Unfortunately for thi view, Point Hueneme was far in the lead for the next four years and has bee in the lead (or very nearly so) for every year up to 1938, when La Jolla cam up strongly again. Also in the first ten years no week averaged higher tha tens of thousands and few were above thousands at either station in Januar and December. Surely it might be supposed that light production would always occur in those months. But in December, 1932, La Jolla showed a las week average of more than 200,000 cells per liter, which carried over throug

e first week of January, 1933. Again in 1936 and in 1939 La Jolla produced
gh week averages in January. No less impressive in dealing with plankton
atoms is the increase in accuracy of understanding of the data obtainable
y a daily frequency of collecting or observation. In our records for one pulse
hich were analyzed several years ago it was found that a complete change
leading species occurred near the middle of the pulse although the graph
r the total population of diatoms showed no break in the curve. In reality,
e occurrence of this pulse was based on the overlapping occurrence of pulses
two species, one succeeding the other in numerical dominance. Many times,
making up week averages from daily records (both for total populations
d for individual species), observations made only once a week would have
issed the large catches, missing also any indication of a distinctive pulse,
t to mention many other incident phenomena. The unavoidable conclusion
that attempts to coördinate and correlate chemical and physical data with
cords of changes in activity or productivity of diatoms are likely to be
ossly misleading if based on observations made at intervals longer than one
y. Certainly they are not even dependably suggestive.

Extremely low production of diatoms tended to appear in August (La Jolla
ly), November, and December, but week averages of less than one hundred
lls per liter for some weeks in other months may be found in different years,
rely and irregularly. A remarkable feature of this matter of low production
diatoms is that the thirty-second week of the year (August) was invariably
or very near the lowest limit of production for eleven successive years at
a Jolla, although August was not notably deficient at Point Hueneme in most
those years. Apparently this strange condition is due to some climatic (or
milarly general) condition which was operative at La Jolla and not at Point
ueneme. Such vagaries as this are especially interesting to me because of
e possibility that they may be clues to important differences in conditions
verning production at the two stations. After 1932 the distinction was less
rominent.

Although the range of production of diatoms resembles that of dinoflagel-
tes by extending from nothing to millions per liter for single catches at both
ers, the general aspect of productivity is such that one expects at least some
ndreds of diatoms per liter in a catch at any time of year, and some tens of
ousands per liter in the generally productive period from March to July.
lso, the general appearance of the records indicates that week averages of
ndreds of thousands per liter are to be expected in some part of the period
most years.

Incomplete studies of food-chain relationships of diatoms (and dinoflagel-
tes) have indicated direct use by sardines and mussels, but no approach to
termination of values has been made.

In oceanographic literature it has become almost a maxim that higher lati-
des are more productive of marine life than others. Diatoms, in particular,
ve been selected by various authors to illustrate their assertions that this
true. From the first, this view has been held in doubt at the Scripps Insti-
tion, although not contradicted. Our attitude has been merely that a sweep-
g generalization of this importance requires positive proof. So far as we have
en able to deal with this problem, our results to date have strengthened our
ubt, although we do not think that enough evidence of the right kind has
en accumulated either for or against the idea. We hoped to get pertinent
formation by establishing a subarctic daily collecting station at Scotch Cap
ght in the Aleutian Islands, but observations carried over parts of eight
ears (five full years) have yielded indications so directly contrary to that

idea that we cannot accept their evidence except for supplementary use. A
parently the Scotch Cap station is in one of those localities rarely if ev
characterized by large production of diatoms. It is true that Scotch Cap ma
be fairly representative of high latitudes because of a productivity near t
average, but we need more evidence from highly productive localities as we
as from poorly productive ones before we can form a dependable idea of wh
diatom production in high latitudes really is. By many observers too mu
reliance has been placed in cursory observations on populations which ma
have existed for only a few days or weeks and then only at surface leve
No true comparison can be made until observations are carried through
series of years at a number of stations in both high and low latitudes at leve
from the surface to fifty or sixty meters, by sampling with high frequency
not less than ten-meter intervals. Aside from the relative thinness at Scot
Cap, the Scripps Institution has other records bearing on the question. T
cruises by the United States Coast and Geodetic Survey in Alaskan wate
yielded surface collections which showed positively that extremely large nu
bers of diatoms were produced in certain localities, relatively few, howeve
Cruises by other ships as far south as Peru have obtained surface catch
showing that at a number of points between California and the equator di
toms may appear at times in numbers exceeding a million cells per liter. Th
is to say, so far as we have been able to obtain evidence, high production
diatoms at the surface is not restricted to high latitudes. Off the Californ
coast some of our largest catches of diatoms have been obtained at twenty
forty meters below the surface. High latitudes never have too much light
the surface and at best there is enough obliquity of the rays to cause rap
reduction of penetration of light. In low latitudes light is never too little a
there is never serious interference with light penetration on account of ob
quity. For these physical reasons alone it seems that relative productiveness
high and low latitudes needs thorough investigation before positive concl
sions are reached one way or the other.

As early as 1926 the Institution found at stations no farther than five a
ten miles from its pier that diatoms might be almost or quite absent from t
surface although present in large abundance at one or more levels sampl
below. In that year large numbers were found at the forty-meter level of t
ten-mile station when only a few were at the surface. In 1927 at the five-m
station large numbers were found at thirty meters when the numbers at t
surface were negligible and on another day much larger numbers were fou
at thirty and forty meters with small numbers appearing at levels from t
surface to thirty meters. In this connection may be mentioned again the ri
of drawing positive conclusions on limited evidence. In 1926 the ten-mile st
tion was most productive, all levels considered, suggesting the idea that wate
offshore were more productive, especially at lower levels. In 1927 the five-m
station was much more productive, collecting in both years being done in Ju
and July.

On six cruises of 1938, sailed on alternate months from February, coveri
territory from Cape Arguello to San Diego, the evidence was fairly consiste
throughout that better production of diatoms occurred at twenty or mo
miles offshore than within ten or fifteen miles of shore except for two high
productive stations in June near Santa Cruz and San Miguel islands. It w
found also that the largest abundance was more frequently below than at t
surface at single stations, although the surface level yielded largest numbe
at some stations on some cruises. Collections of notable size were taken as f
as one hundred miles from shore, thus showing definitely that wide spaces

l as considerable depths must be included in investigations of phytoplank- production and the conditions regulating it. From the same cruises we e strong evidence, also, that the seasonal differences in production of toms offshore correspond very well with those of most years as revealed daily catches at inshore stations, the tendency being to greatest production he April to June period. Unfortunately most of the cruises were made at es of slack production inshore or on the decline of an inshore pulse. If the e of each cruise could have been made at exactly the time of an inshore se, the larger numbers in the offshore catches might have made it easier trace resemblances with confidence. However, the resemblances between sonal changes of abundances at inshore and offshore stations are so close to make it appear certain that inshore collections correctly indicate sea- al changes in production for the whole territory in most years, if not in all. smuch as 1938 was the most productive year, or nearly so, at both La Jolla l Point Hueneme, it is probable that offshore production was also unusu- y high. In the thinly productive years of 1926 and 1931 it might have been icult to trace any kinds of relationships.

)ther investigators of phytoplankton may be interested in the fact that re than fifty papers have been published dealing directly with the phyto- nkton material accumulated by the Scripps Institution in twenty years l that these have been supplemented by fifteen papers dealing with it less ectly. Most of these papers are out of print, but some are still available for hange.

lthough a number of other things might be said about the results obtained in process of being obtained by twenty years of phytoplankton researches the Scripps Institution of Oceanography, I think that enough may have n said to indicate that no matter how busy we have been and how many blems we have attacked with variable success, there is still plenty to do. I se with a simple list of the more prominent or more significant series of lections and studies up to date. At the Institution pier daily collections e continued for twenty years; at Point Hueneme for nearly twenty years, be closed out soon. Daily collections at Scotch Cap ran for eight years, at Farallon Islands for five years, at Balboa, California, for three years, at eanside, California, for five years, and at a few other points for some months ore being closed out. A number of short cruises by the Institution in local ters yielded some valuable data before Director H. U. Sverdrup instituted bimonthly cruises of 1938, carried to seaward from several points on the lifornia coast. In 1939 a cruise to the Gulf of California obtained valuable a, levels to sixty meters' depth being regularly sampled, yielding nearly ee hundred and fifty catches. A cruise somewhat like those of 1938 but ering two hundred miles to sea in a half-dozen lines between the Columbia ver and Cedros Island has just been completed, bringing in about five hun- d catches which will be examined soon. In earlier years the United States ast and Geodetic Survey not only collected for the Institution in Alaskan ters but also in the California region. The United States Navy contributed eries of collections made between California and Australia. The late E. W. ripps gave two or three series of collections made by his yacht. Also the stitution has made use of collections contributed by Captain G. Allan Han- k of Los Angeles and by Templeton Crocker of San Francisco, as well as ne others.

Contribution No. 103

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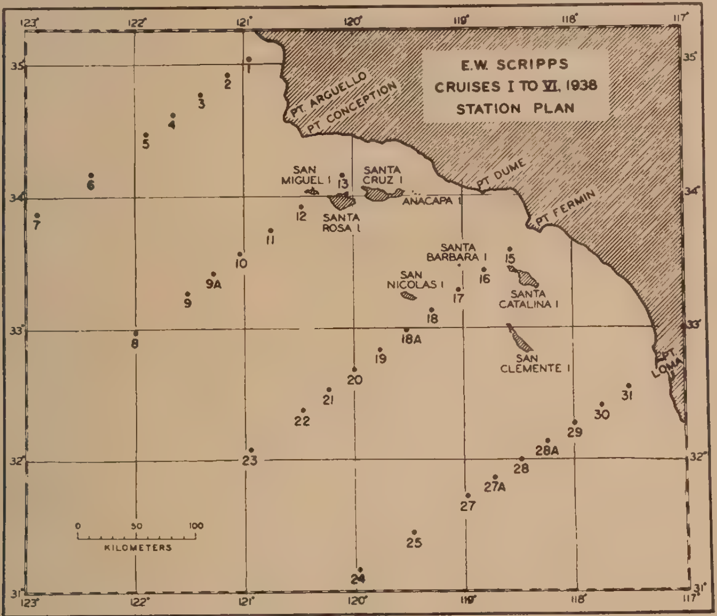
HARACTER OF THE CURRENTS OFF SOUTHERN CALIFORNIA

By Richard H. Fleming

VITHIN an area extending from 31° N to 35° N and approximately 150 miles) sea, systematic oceanographic observations were carried out by the Scripps nstitution of Oceanography on three cruises in the spring and early summer f 1937, and six cruises in 1938. The general locations for the collection of ata are shown in figure 1. Because of stormy weather and unfavorable condi-



E.W. SCRIPPS
CRUISES I TO VI, 1938
STATION PLAN
123°
122°
121°
120°
119°
118°
117°
35°
34°
33°
32°
31°
PT. ARGUELLO
PT. CONCEPTION
PT. DUME
PT. FERMIN
PT. LOMA
SAN MIGUEL I
SANTA CRUZ I
ANACAPA I
SANTA ROSA I
SANTA BARBARA I
SAN NICOLAS I
SANTA CATALINA I
SAN CLEMENTE I
1
2
3
4
5
6
7
8
9
9A
10
11
12
13
15
16
17
18
18A
19
20
21
22
23
24
25
27
27A
28
28A
29
30
31
0
50
100
KILOMETERS

Fig. 1. Station plan for the investigations carried out by the *E. W. Scripps* in 1938. The same general plan was followed in 1937 by the *Bluefin.*

ions it was sometimes impossible to occupy all these stations. The investiations in 1937 were carried out with the coöperation of the California State 'isheries Laboratories of the Division of Fish and Game, and their vessel, he *Bluefin*, was used to make the three cruises (Sverdrup and Fleming, in ress). In 1938 the *E. W. Scripps* was placed in commission and made six ruises at two-months intervals (Sverdrup and staff, in press). The 1937 inestigations showed that the currents associated with the distribution of ensity were largely within the upper 500 meters, and therefore in 1938 the bservations were usually restricted to the upper 600 meters. Besides temerature observations and salinity determinations, analyses for the content of issolved oxygen were carried out on all water samples collected. In addition, hosphate determinations were made on the first three cruises in 1938 and the rogram was enlarged to include phytoplankton collections and zoöplankton amples.

The present discussion of the circulation will be based largely upon the 938 observations, as these cover the entire year. Within the area covered by hese studies the pattern of flow at and near the surface is very complicated.

The reasons for this will be dealt with later. However, the general features may be described as follows. In the offshore area there is generally a transport to the south or southeast which represents the eastern portion of the California Current. Between the California Current and the coast there is commonly a flow to the north, termed the California Counter Current. At least a part of this current usually turns inshore and flows to the south again along the coast. During the spring and early summer months the Counter Current may disappear at the surface, but at lower levels the northward transport near the coast persists throughout the year. Figure 2 shows the generalized pattern of flow at the surface.

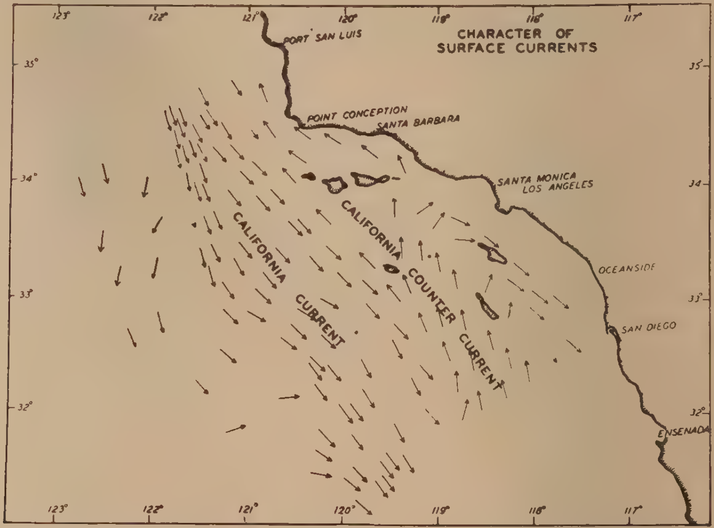


Fig. 2. Generalized pattern of surface flow off the coast of Southern California and names applied to the currents.

The surface currents, associated with the distribution of density observed on the six cruises in 1938, are shown in figures 3 to 8. It can readily be seen that the Counter Current has its greatest development during the winter months, when it extends northward as far as observations were obtained (figs. 3 to 8). During the spring months (fig. 4) the Counter Current apparently disappears entirely at the surface under the influence of the northwest winds which are strongest at this time of year. During the summer and autumn there is a gradual reëstablishment of surface flow to the north. It is striking that the pattern of flow in the offshore area within the California Current is extremely irregular. In some cases there are bands of high velocity, as is shown in figure 5, and in all cases where relatively complete series of observations were obtained, there is evidence of the presence of eddies. Lack of observations extending farther west and south make it impossible to determine the nature of the inflow from the west, particularly in the southwestern portion of the area investigated, which is shown on most of the charts.

Between the California Current and the Counter Current there is a dynamic low. Examination of figures 3 to 8 shows that this trough usually extends southward from the area off Point Conception. During the spring months

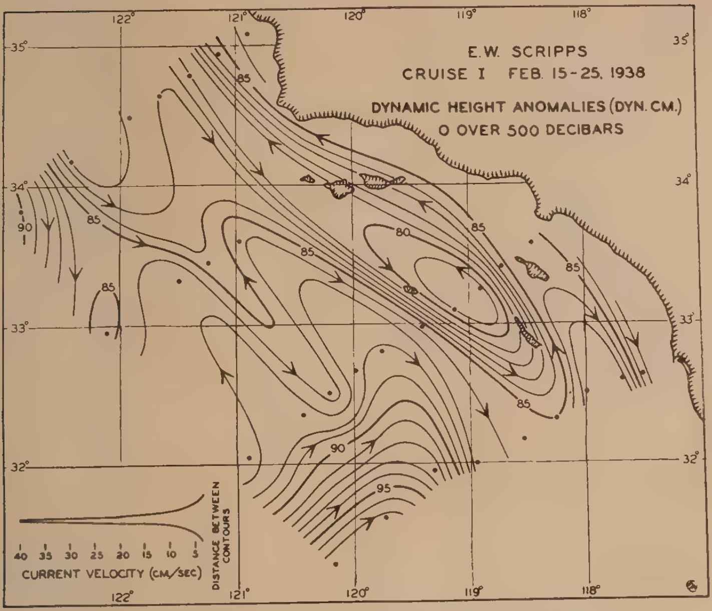

E.W. SCRIPPS
CRUISE I FEB. 15-25, 1938
DYNAMIC HEIGHT ANOMALIES (DYN. CM.)
0 OVER 500 DECIBARS
122°
121°
120°
119°
118°
35°
34°
33°
32°
85
90
80
95
40 35 30 25 20 15 10 5
CURRENT VELOCITY (CM/SEC)
DISTANCE BETWEEN CONTOURS

Fig. 3. Dynamic height anomalies in dynamic centimeters, 0 over 500 decibars. February 15–25, 1938.

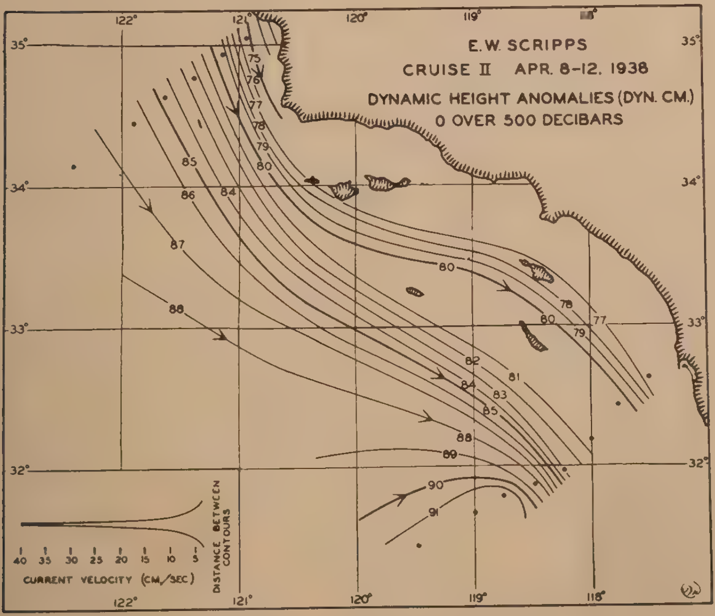

E.W. SCRIPPS
CRUISE II APR. 8-12, 1938
DYNAMIC HEIGHT ANOMALIES (DYN. CM.)
0 OVER 500 DECIBARS
122°
121°
120°
119°
118°
35°
34°
33°
32°
73
76
77
78
79
80
85
86
84
87
88
82
81
83
89
90
91
40 35 30 25 20 15 10 5
CURRENT VELOCITY (CM/SEC)
DISTANCE BETWEEN CONTOURS

Fig. 4. Dynamic height anomalies in dynamic centimeters, 0 over 500 decibars. April 8–12, 1938.

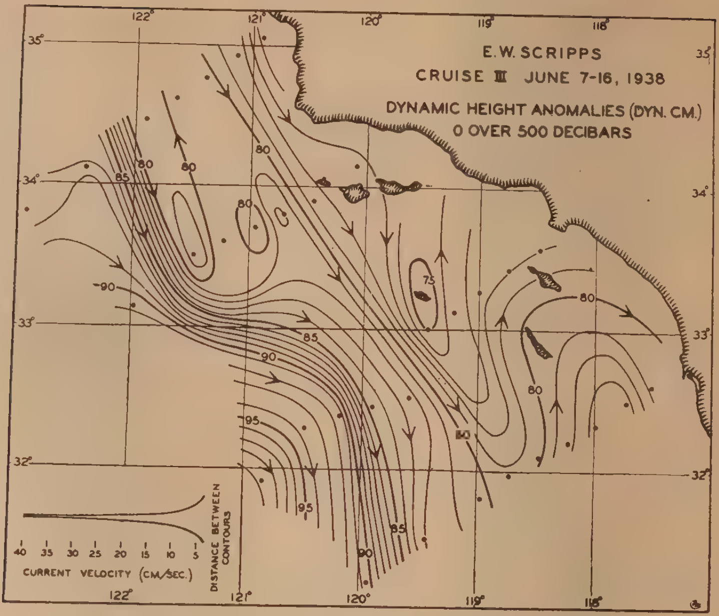

E.W. SCRIPPS
CRUISE III JUNE 7-16, 1938
DYNAMIC HEIGHT ANOMALIES (DYN. CM.)
0 OVER 500 DECIBARS
122°
121°
120°
119°
118°
35°
34°
33°
32°
80
85
90
95
75
40 35 30 25 20 15 10 5
CURRENT VELOCITY (CM/SEC.)
DISTANCE BETWEEN CONTOURS

Fig. 5. Dynamic height anomalies in dynamic centimeters, 0 over 500 decibars. June 7–16, 1938.

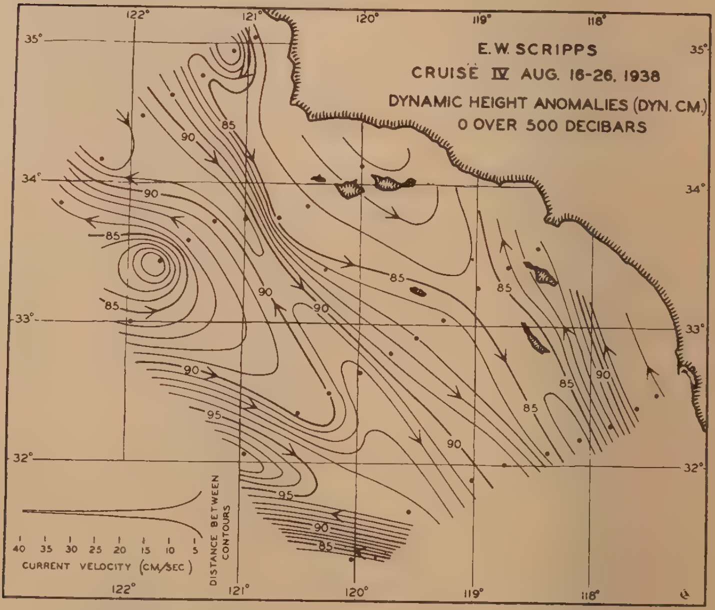

E.W. SCRIPPS
CRUISE IV AUG. 16-26, 1938
DYNAMIC HEIGHT ANOMALIES (DYN. CM.)
0 OVER 500 DECIBARS
122°
121°
120°
119°
118°
35°
34°
33°
32°
85
90
95
40 35 30 25 20 15 10 5
CURRENT VELOCITY (CM/SEC)
DISTANCE BETWEEN CONTOURS

Fig. 6. Dynamic height anomalies in dynamic centimeters, 0 over 500 decibars. August 16–26, 1938.

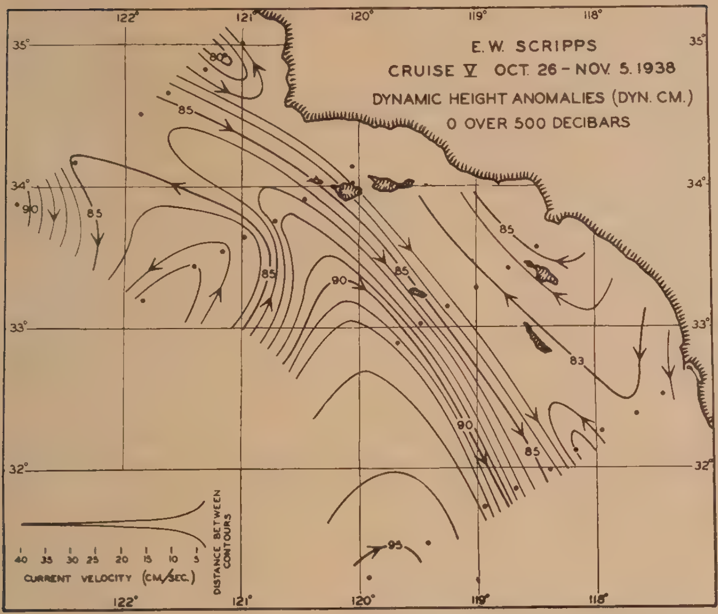

E.W. SCRIPPS
CRUISE V OCT. 26 - NOV. 5. 1938
DYNAMIC HEIGHT ANOMALIES (DYN. CM.)
0 OVER 500 DECIBARS
122°
121°
120°
119°
118°
35°
34°
33°
32°
80
85
90
83
95
40 35 30 25 20 15 10 5
CURRENT VELOCITY (CM/SEC.)
DISTANCE BETWEEN CONTOURS

Fig. 7. Dynamic height anomalies in dynamic centimeters, 0 over 500 decibars. October 26–November 5, 1938.

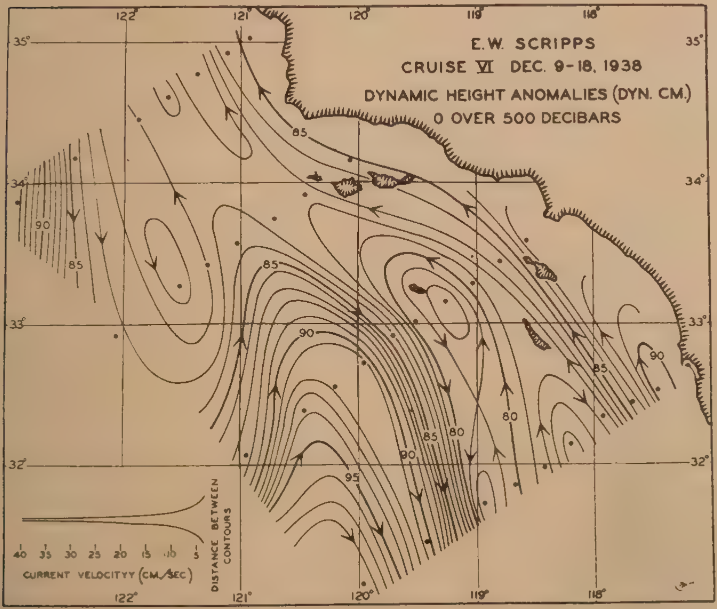

E.W. SCRIPPS
CRUISE VI DEC. 9-18, 1938
DYNAMIC HEIGHT ANOMALIES (DYN. CM.)
0 OVER 500 DECIBARS
122°
121°
120°
119°
118°
35°
34°
33°
32°
85
90
80
95
40 35 30 25 20 15 10 5
CURRENT VELOCITY (CM/SEC)
DISTANCE BETWEEN CONTOURS

Fig. 8. Dynamic height anomalies in dynamic centimeters, 0 over 500 decibars. December 9–18, 1938.

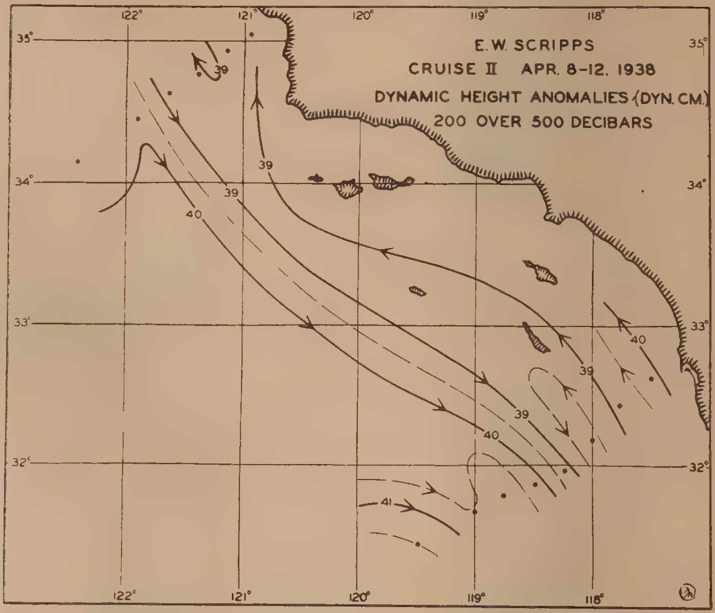

E.W. SCRIPPS
CRUISE II APR. 8-12. 1938
DYNAMIC HEIGHT ANOMALIES (DYN. CM.)
200 OVER 500 DECIBARS
122°
121°
120°
119°
118°
35°
34°
33°
32°
39
40
41

Fig. 9. Dynamic height anomalies, 200 over 500 decibars. Contour interval 0.5 dynamic centimeters. April 8–12, 1938.

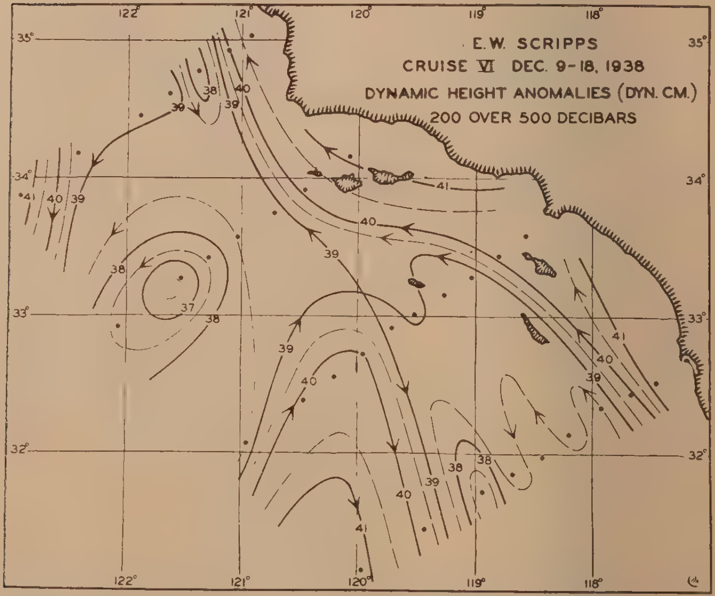

E.W. SCRIPPS
CRUISE VI DEC. 9-18, 1938
DYNAMIC HEIGHT ANOMALIES (DYN. CM.)
200 OVER 500 DECIBARS
122°
121°
120°
119°
118°
35°
34°
33°
32°
37
38
39
40
41

Fig. 10. Dynamic height anomalies, 200 over 500 decibars. Contour interval 0.5 dynamic centimeters. December 9–18, 1938.

is trough moves in toward the coast and corresponds to the zone of active pwelling which occurs at this time of year. In the southern part of the area e contours turn on themselves and indicate that at least part of the surface ater in the Counter Current is from the trough which has turned inshore nd to the north. Even when there is no indication on the chart of such a flow fig. 6), the character of the surface water in the Counter Current indicates at it is related to that found in the offshore portion of the trough which has owed farther to the south before turning north.

On the basis of the pattern of flow it is possible to designate three zones ithin which the conditions are more or less uniform. First, there is an Offhore Zone, corresponding to the California Current, where the surface temeratures are relatively high and the salinity low, and where the convection ayer is relatively thick. Second, there is the Trough Zone, within which the urface temperatures are low and the salinity high, as would be expected from he effects of upwelling. In this zone the convection layer is very thin or may e entirely absent. Third, there is the Counter Current or Coastal Zone, which s characterized by temperatures approximately the same as those in the offhore water, but in which the salinity is intermediate between that of the ther two zones and the convection layer is rather thin. Because of the shifts n the currents the conditions encountered at any location may show marked hanges in the course of the year which are not related to local climatic ariations.

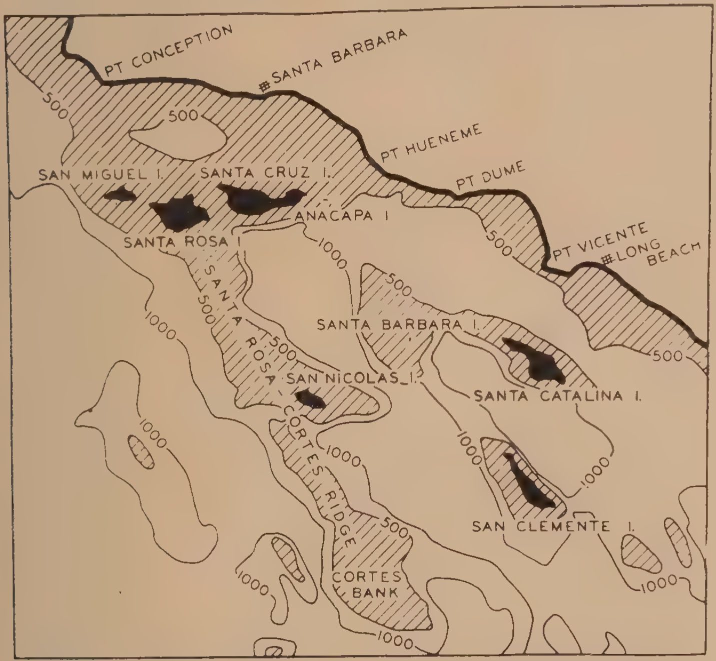

PT CONCEPTION
SANTA BARBARA
PT HUENEME
PT DUME
PT VICENTE
LONG BEACH
SAN MIGUEL I.
SANTA CRUZ I.
ANACAPA I
SANTA ROSA I
SANTA ROSA
SANTA BARBARA I.
SAN NICOLAS I.
SANTA CATALINA I.
CORTES RIDGE
SAN CLEMENTE I.
CORTES BANK
500
1000

Fig. 11. Outstanding features of the submarine topography off Southern California. Depths in meters. (After Sverdrup and Fleming.)

The currents associated with the distribution of density are largely retricted to the upper layers and most of the flow as described above occurs in the first 100 meters. At a depth of 200 meters we find a somewhat differen pattern. Offshore there is still some indication of transport to the southeast but the northerly transport near shore is much more conspicuous than a shallower depths. The latter has been termed the deep Coastal Current and i a part of the Counter Current. It may be seen from figures 9 and 10 that th northward-flowing Deep Coastal Current extends farther offshore and tha it persists even during the spring months when there is no northward transport at the surface.

The pattern of flow within the area covered by these investigations i apparently rather permanent, but at present the available data do not permi

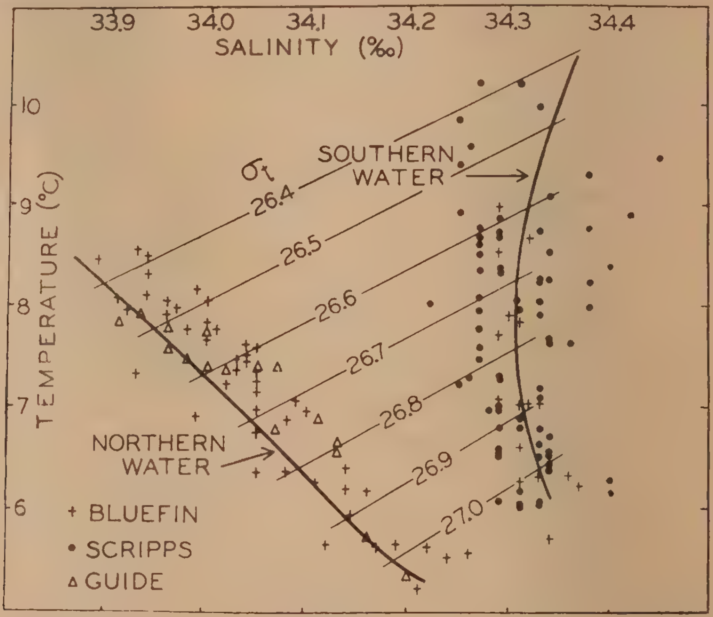


Fig. 12. Scatter diagram showing the temperature and salinity observations used to define the characteristic T-S curves from Northern and Southern Water. (After Sverdrup and Fleming.)

us to account completely for the nature of the flow. The southeasterly flo offshore is part of the California Current and is therefore part of the Nort Pacific gyral, which is probably maintained by large-scale climatic agencies The bands of high velocities sometimes encountered in this current have bee shown by Sverdrup (1938) to be associated with the local northwest winds an the resultant upwelling. The fact that the Counter Current system persist in the absence of southerly winds indicates that it may be somewhat simila in character to the inshore countercurrent found on the eastern coast of the United States. The topography of the area and the shape of the coast lin undoubtedly play important parts in determining the pattern of flow. At depth of 500 meters there is a peninsula extending south-southeast from the Channel Islands (figure 11). Even at shallower depths this peninsula is almost continuous and consequently the flow to the north must take place outside this ridge or turn on itself within the submarine embayment. It is characteristi of the winds that they are strong north of Point Conception and outside o ie Santa Rosa-Cortes ridge. Consequently the flow between this ridge and the iore cannot be markedly affected by the local winds. This may, in part at ast, account for the fact that off southern California the Counter Current in persist at the surface for the greater part of the year. However, at and eyond Point Conception the strong northwest winds oppose the northward ow and the water of the Counter Current may be forced to flow inshore and the south.

The area covered by these investigations is one of rather large lateral differ- ices in the distribution of properties. Part of these must be attributed to the

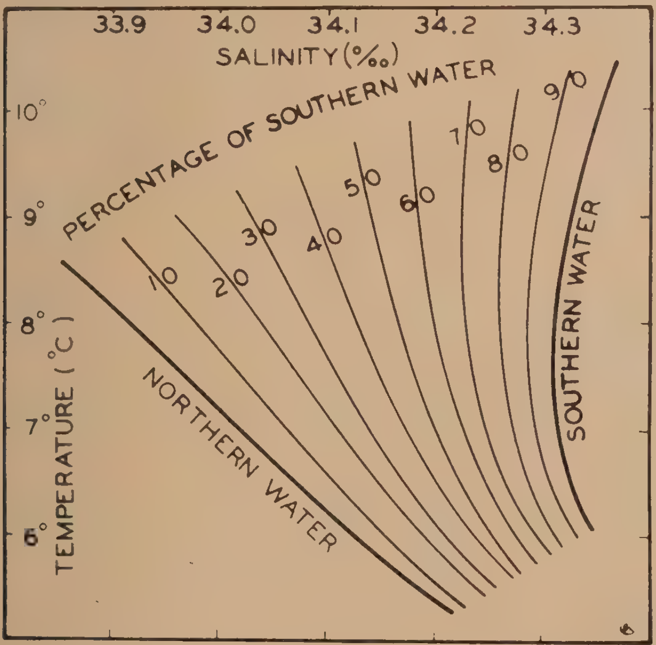


Fig. 13. Diagram showing the T-S curves of water containing various percentages of Southern Water. This diagram is also used to determine the percentage of Southern Water in any water sample of known temperature and salinity. Constructed on the assumption that mixing between the extreme types takes place along σ_t surfaces. (After Sverdrup and Fleming.)

radients associated with the currents, and, near the surface, the upwelling ntributes to the differences. However, even at lower levels marked gradients e found and these are due to the differences in the character of the offshore ater of the California Current and the water of the Deep Coastal Current. t any temperature less than 10° the water of the Deep Coastal Current has higher salinity and lower oxygen content. On the basis of the observations 1937 and earlier collections, T-S curves, characteristic of the offshore water ndicated as Northern Water), and inshore water (indicated as Southern ater), were constructed (fig. 12). T-S curves for virtually all stations corre- ond to either of these two curves or will fall between them. On the assump- on that mixing takes place along σ_t surfaces, it is possible to construct a agram showing the percentage of Southern Water in any water sample on

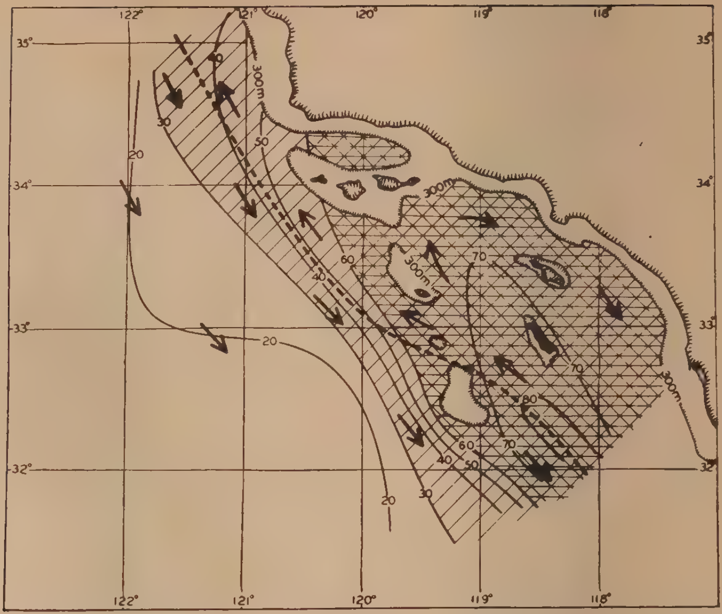

122°
121°
120°
119°
118°
35°
34°
33°
32°
300m
20
30
40
50
60
70
80

Fig. 14. Chart showing the percentage distribution of Southern Water between 200 and 400 meters. Averages of two cruises in 1937. Arrows indicate the direction of flow. (After Sverdrup and Fleming.)

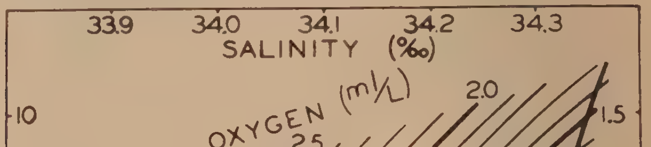


Fig. 15. Diagram showing the "normal" oxygen content of Northern and Southern Water, and mixtures of the two, as a function of the temperature and salinity. Mixing of the extreme types is assumed to take place along σ_t surfaces. (After Sverdrup and Fleming.)

basis of its temperature and salinity (fig. 13). In this way, profile and rts were constructed representing the distribution of the percentage of thern Water. These showed that there was a very good regional pattern listribution of the two types of water except where it was modified by ies. An example of the horizontal pattern is shown in figure 14. From this an be seen that within the Counter Current system the percentage of thern Water decreases along the line of flow. On the other hand, the con- t of Southern Water increases along the line of flow in the southerly cur- t in the offshore area. As the oxygen content of the Northern and Southern ters differs appreciably it is possible to prepare a diagram (fig. 15) which ws the "normal" oxygen content of mixtures of the two water masses. ıming, first, that mixing takes place along σ_t surfaces, and second, that

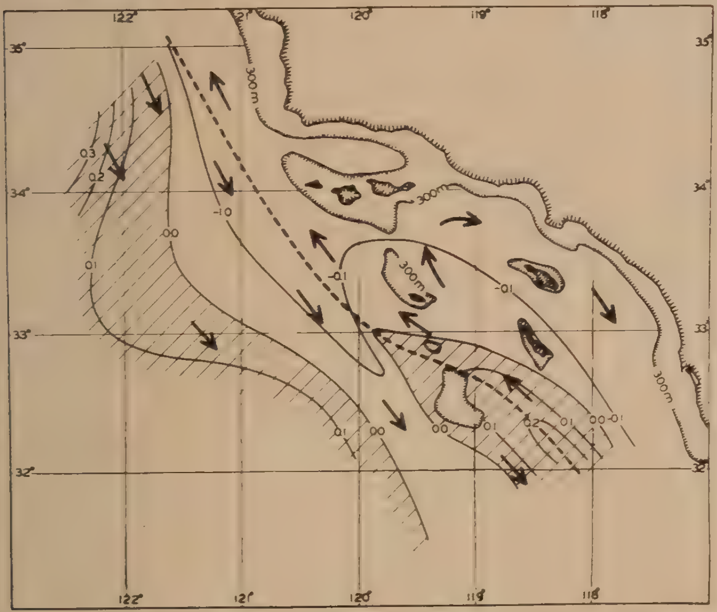


Fig. 16. Chart showing the distribution of oxygen anomalies between 300 and 400 meters. Average of two cruises in 1937. Arrows indicate the direction of flow. (After Sverdrup and Fleming.)

re is no consumption. Comparison of the "normal" oxygen contents and observed quantities showed that consumption does take place along the e of flow (fig. 16).

A detailed examination of the 1937 data has been made and on the basis of distribution of Southern Water and the velocity it was possible to compute lateral coefficient of eddy diffusivity, which gave values of about 2×10^6 ^{2}/sec. From a study of the oxygen anomalies, the total oxygen consumption s computed to be between 1.1 and 2.2 liters per day in a water column of e square meter cross section extending from 50 meters to a depth of 700 ters. This corresponds to a minimum value for the production in the upper meters of between 9.8 and 19.6 grams per square meter per day of wet nkton.

The very active lateral mixing which takes place in this area can readily be determined because of the differences in the properties of the water. T mixing is brought about by eddies of variable dimensions, some of which as much as 50 kilometers in diameter. These frequently show up on the cha not only of dynamic topography, but also those showing the distribution properties. It is of interest to note that the existence of these eddies is c firmed by studies of the distribution of plankton. Within the upper layers eddies may contain types and quantities of plankton altogether different fr those in the water surrounding them. Frequently, eddies composed of Coun Current water were found in the offshore area, and in a few places eddies offshore water were found in the coastal area.

In conclusion, it is of interest to consider the relation of the southwa flow in the offshore area to that of the California Current as a whole. Exa nation of the 1937 data showed that the southerly transport within the a of these investigations could not represent more than about 10 or 20 per c of the bulk of the transport of the California Current.

Assistance in the preparation of these materials was supplied by the pers nel of the Works Progress Administration Official Project No. 665–07–3–1

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[Contribution from the Scripps Institution of Oceanography, New Series, No. 10

Contribution No. 104

(Reprinted from Proceedings of the Sixth Pacific Science Congress, Volume III, held at Berkeley, nford and San Francisco July 24 to August 12, 1939.)

COMPOSITION OF PLANKTON AND UNITS FOR REPORTING POPULATIONS AND PRODUCTION

By Richard H. Fleming

ie following discussion deals with two general problems: first, the ratios tween certain essential constituents of marine organisms; and second, ra- nal units for reporting quantities of plankton and the numerical relation- ips between these units. High accuracy cannot be claimed for either the tios or the numerical relationships between various types of plankton units. ie available data show a considerable range and, furthermore, the quantita- e relationships will depend somewhat on the method by which they are mputed. Consequently, although the method of treatment is valid, the merical values must be considered as tentative and subject to some revision ien additional data are available.

In 1934, Redfield pointed out that the proportions of carbon, nitrogen, and osphorus in plankton organisms were rather constant and that these ratios rresponded closely to those for sea water. Since then, Seiwell (1935), Cooper 935, 1937–38, and 1938*a*) and von Brand (1935) have supplied additional formation on these ratios which differ somewhat from those given by Red- ld. Furthermore, Cooper (1938*b*) has pointed out that Redfield's ratios for ι water must be modified because of the salt error in the determination of osphate phosphorus which was not taken into account in the earlier estima- ns. From the available data, which included certain material given by nogradov, analyses were selected for the calculation of the ratios of C:N:P both zoöplankton and phytoplankton. In making this selection certain de- rminations which showed pronounced departures from the general average re omitted. Some adjustments were necessary in order to determine the best erage ratios for all three elements, as in most cases only a single ratio, that either C:N, N:P, or C:P was determined. In this discussion "carbon" will taken to mean organic carbon exclusive of carbon which may be present in lcareous structures. The final ratios obtained in this way are shown in ole 1.

TABLE 1

Ratios of C:N:P in Plankton and Sea Water

Authority	Material	(By weight)				(By atoms)		
		C	N	P	C:N	C	N	P
dfield (1934).....	Plankton........	53.2	8.2	1	6.5	...	..	..
dfield (1934).....	Sea water........	54.1	9.0	1	...	140	20	1
oper (1938*b*)......	Sea water........	....	6.8	1	...	...	15	1
w estimates....	Phytoplankton...	42	7	1	...	...	..	..
	Zoöplankton.....	40	7.4	1	...	...	..	..
	Average.........	41	7.2	1	...	106	16	1

As the difference between the average ratios for zoöplankton and phyto- ankton were so small, it was decided that they were not significant because the wide spread of individual determinations, and consequently a combined erage set of ratios will be used in the following discussion. It may be seen om table 1 that the new ratio of N:P in plankton corresponds very closely the ratio for sea water proposed by Cooper (1938*b*).

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Redfield laid particular emphasis upon the fact that the ratios of C :N
in plankton were virtually the same as the values he obtained for sea wate
He offered two possible explanations for this agreement, which must still
considered, as the new averages for plankton are very close to those for s
water. Redfield suggests either that the ratios in sea water are ideally suit
for the organisms living in it, or that the character of the population, of whi
different species may require these elements in different proportions, is
controlled by the amounts available that all are ultimately reduced to thre
hold values. A third possibility, not offered by Redfield, which must be co
sidered is that with respect to those elements which are present in very lo
concentrations the phytoplankton utilize all the material they can obtain.
we assume that there is no difference in the absorption of the different ion
they will then be removed from the water in the same proportion as the rati
of their concentrations. If this is the fact, the proportions in the phytoplan
ton, at least of nitrogen and phosphorus, would correspond to the ratios in t
water. If this is true, the ratio of N :P in phytoplankton would vary somewh
if there are any variations in the relative amounts present in the wate
Evidence that the ratio in diatoms may depend upon the relative quantiti
in solution has been found by Sargent (1939). Although the ratios in ph
toplankton may be determined by the supply, the composition of zoöplankton
not necessarily determined by such a factor. Consequently there may be si
nificant differences between the ratios in animal and plant plankton, althoug
these do not show up in the averages given in table 1. Such possible differenc
should be kept in mind.

Accurate knowledge concerning the ratios of various elements in plankto
is important in many connections. If the ratios between certain elements, suc
as those for C :N :P given in table 1, are constant, they can be used in mar
ways. If we are dealing with a given volume of water in which there is
differential gain or loss of materials to the surroundings, the determinatio
of the time variations in the concentration of, say, phosphate, can be used as
measure of the corresponding changes in the carbon and nitrogen in the wate
Furthermore, such ratios would be very helpful in studies of the relati
rates of regeneration of these elements. If we now consider the quantity
plankton, the determination of any one of these elements in the catch will
a measure of the others. When expressing quantities of plankton, howeve
the statement that a plankton catch contains a certain amount of carbon do
not convey any real picture of the volume or quantity of organisms presen
Therefore it is desirable to know the relationships which exist between quant
ties of carbon, nitrogen, and phosphorus and certain units which have bee
used in plankton research. Furthermore, unless such relationships are know
conventional methods of reporting plankton cannot be related quantitativel
either to their contents of certain chemical elements or to changes in t
concentration of these elements in the water. Finally, calculations of the tot
production in a given interval, based on the utilization of essential element
such as those made by Cooper (1933 and 1938*c*), require knowledge of t
numerical relationships between the variable elements and the correspondin
amounts of plankton. Estimates of the total production in a given interv
based on the utilization of any essential element assumes that regeneration
negligible. If it is not, a correction must be applied for this factor. The chang
in population of a given water mass need not correspond to the productio
in the same time interval, because it is possible that a considerable quantity
the element, used as the basis of the calculation, has been excreted or release
in a form not detected in the analysis of the water. Furthermore, plankto

oduced in a given volume of water may be removed by pelagic organisms
iich have consumed this material and then migrated elsewhere.

Plankton populations are usually expressed by enumeration of the numbers
different types of organisms obtained from a certain volume of water. Be-
use of the tremendous range in size, shape, and composition of the organisms,
ch enumeration gives no measure of the quantity of carbon, nitrogen, or
osphorus, unless the size and composition of the individual types of organ-
ns are known and taken into account. One approach to a quantitative
pression of the amount of plankton which may show some relationship to its
ntent of, say, nitrogen is to determine the volume or weight of the plankton
tch. Various methods for determining the volume of plankton have been
ggested, such as allowing the material to settle in graduated cylinders or
centrifuging. Such methods are bound to yield variable results, depending
t only upon the technique followed, but also upon the nature of the indi-
lual plankton samples. Another method which should yield a fairly good
lationship to the essential elements is that of determining the dry weight of
e plankton samples. Even here there will be a wide range because of the
fferences in the relative proportions of inorganic skeletal material in differ-
t types of organisms. When dealing more specifically with phytoplankton,
e problem is not quite so complicated. Harvey (1934) has shown that the
ytoplankton population can be expressed in terms of plant-pigment units,
d Harvey, Cooper, Lebour, and Russell (1935) have suggested the use of
atoms of "average cell contents" to express the quantity of phytoplankton.
ıerefore, with respect to phytoplankton it is possible to use quantitative
iits which will bear a much closer relationship to their content of essential
ements. In the rest of this discussion, various quantitative relationships are
esented which relate the different units for reporting plankton and their
ntent of carbon, nitrogen, and phosphorus.

Starting with the relationship that the C:N:P ratios in marine plankton are
:7.2:1, it is possible to determine quantitative relationships between these
ements and various units for reporting quantities of plankton. Harvey,
oper, Lebour, and Russell (1935) determined the phosphorus content of
ytoplankton samples the content of which in plant-pigment units had been
easured and obtained an average of 1 mg. of phosphorus for every 12,500
ant-pigment units. Furthermore, they found that 1 mg. of phosphorus was
uivalent to 50 × 10^6 diatoms of "average cell contents." One diatom of
erage cell content is shown to be equal to 3 cells of *Rhizosolenia alata,* 3½
lls of *Rhizosolenia shrubsolei,* or 20 cells of *Skeletonema costatum.* Sargent
939) has found in culture experiments that the minimum phosphorus con-
nt of *Nitzschia closterium* is 1 mg. in 14,000 × 10^6 cells. From these relation-
ips it is possible to calculate the numerical equivalents shown in table 2.

Atkins (1923) introduced the unit "wet plankton" when estimating the pro-
ıction of plankton in the English Channel from the utilization of phosphate
ıosphorus. The quantitative relationship used by him was that 1 mg. of
ıosphorus was equivalent to 1520 mg. of "wet plankton." Unfortunately,
is relationship was not directly determined for plankton, but was based
analyses of seaweed, and hence calculations actually represent the equiva-
nt quantity of wet seaweed. Cooper (1933 and 1938*c*) has computed the
oduction in terms of "wet plankton" from the consumption of phosphorus,
rbon, and nitrogen and the release of oxygen. Gilson (1937) has recomputed
eiwell's estimate (1935) based on oxygen consumption below the photosyn-
etic zone in these terms. The same method has been used by Sverdrup and
leming (in press).

TABLE 2

PLANKTON EQUIVALENTS

Ratios, C:N:P = 41:7.2:1 (by weight)

	Carbon 1 mg.	Nitrogen 1 mg.	Phosphorous 1 mg.	Plant pigment 1 unit	Diatoms avg. conts. 1 cell	"Wet plankton" 1 mg.	Dry plankton 1 mg.	Settling volume 1 ml.	Displacement volume 1 ml.	Oxygen equivalent 1 ml.
Carbon (mg.)	1	5.7	41	3.3×10^{-3}	0.8×10^{-6}	0.027	0.44	1.4	5.6	0.536
Nitrogen (mg.)	0.18	1	7.2	0.58×10^{-3}	0.14×10^{-6}	0.0047	0.0765	0.24	1.0	0.097
Phosphorus (mg.)	0.024	0.14	1	0.08×10^{-3}	0.02×10^{-6}	0.00066	0.011	0.034	0.14	0.013
Plant pigment (units)	305	1,740	12,500	1	250×10^{-6}	8.25	133	412	1690	163
Diatoms, avg. conts. (cells)	1.2×10^{6}	7.0×10^{6}	50×10^{6}	4×10^{3}	1	0.033	0.5×10^{6}	1.5×10^{6}	6×10^{6}	0.6×10^{6}
R. alata (cells)	3.7×10^{6}	21×10^{6}	150×10^{6}	12×10^{3}	3.0	0.10×10^{6}	1.6×10^{6}	5.0×10^{6}	20×10^{6}	2.0×10^{6}
R. shrubsolei (cells)	4.3×10^{6}	24×10^{6}	175×10^{6}	14×10^{3}	3.5	0.12×10^{6}	1.8×10^{6}	5.6×10^{6}	23×10^{6}	2.3×10^{6}
S. costatum (cells)	$24.\times10^{6}$	139×10^{6}	$1{,}000\times10^{6}$	80×10^{3}	20	0.66×10^{6}	11×10^{6}	34×10^{6}	140×10^{6}	13×10^{6}
N. closterium (cells)	341×10^{6}	$1{,}950\times10^{6}$	$14{,}000\times10^{6}$	$1{,}120\times10^{3}$	280	9.2×10^{6}	149×10^{6}	462×10^{6}	$1{,}890\times10^{6}$	183×10^{6}
"Wet plankton" (mg.)	37	211	1520	122×10^{-3}	30×10^{-6}	1	16	50	203	20
Dry plankton (mg.)	2.3	13.1	94	7.5×10^{-3}	1.9×10^{-6}	0.06	1	3.1	12.7	1.2
Settling volume (ml.)	0.7	4.2	30.2	2.4×10^{-3}	0.6×10^{-6}	0.02	0.32	1	4.1	0.4
Displacement volume (ml.)	0.18	1.0	7.4	0.59×10^{-3}	0.15×10^{-6}	0.005	0.08	0.25	1	0.1
Oxygen equivalent (ml.)	1.9	10.6	76.	6.1×10^{-3}	1.5×10^{-6}	0.05	0.8	2.5	10.2	1

ooper's value for wet plankton based on phosphorus consumption corres-
ds with that given in table 2, but the relationship to carbon, nitrogen, and
gen equivalent will differ because the ratios of C : N : P used by Cooper are
7.6 :1. That is, Cooper's "wet plankton" contains more than twice as much
bon as that given in table 2 and hence the oxygen equivalent will differ as
l.

he relationship for dry plankton is based upon the observations of Moberg
25), who determined the nitrogen content of 49 samples of dry, salt-free,
ed plankton. The average nitrogen content was found to be 1 in 13.1 parts
ry plankton.

he relationship for the settling volume is also based on Moberg's observa-
s. The mixed net plankton was placed in graduated cylinders and the
ume of settled material read at the end of 48 hours. These samples were
er washed and dried and their dry weight determined. From 56 such deter-
ations he found that 1 mg. of dry plankton occupied 3.1 ml. (probable
or ± 1.0) when allowed to settle for 48 hours.

he displacement volume relationship is based on observations by Dr.
rtin W. Johnson (unpublished material), who examined 115 net-plankton
ples and determined the settling volume in approximately the same man-
as Moberg. The plankton was then concentrated on a filter and placed
a graduate containing some water. The increase in volume was taken as the
placement volume for that sample. The relationship between settling vol-
e and displacement volume found from the 115 samples was that 1 ml. by
placement was equivalent to 4.1–0.7 ml. by settling. The displacement
ume determined in this way is not the actual volume of plankton, as a
siderable quantity of water must be retained by the plankton.

The oxygen equivalent has been calculated on the assumption that the
idation of 1 atom of carbon requires 2 atoms of oxygen and that the same
ount is released during photosynthesis. Gilson (1937) has pointed out that
h a relationship cannot hold true as the nitrogen in the organisms is also
idized. Gilson suggests that the oxygen equivalent should be 20 per cent
ater.

From the sources described above the numerical equivalents between these
rious units have been computed. These are given in table 2.

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Contribution No. 105

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A CONTRIBUTION TO THE OCEANOGRAPHY OF THE CENTRAL AMERICAN REGION

By Richard H. Fleming

IN A SYMPOSIUM on the currents near the coasts of the Pacific Ocean it is of great interest to discuss the conditions in the Central American region. This area is the meetingplace of three of the great currents of the Pacific, namely, he California Current, the Peru Current, and the Equatorial Counter Current, and it is the place of origin of the Northern and Southern Equatorial Currents. The general pattern of circulation at the surface is as follows. Both the California Current and the Peru Current are deflected westward and the water of the Counter Current turns on itself to augment the flow of the Northern and Southern Equatorial Currents. The generalized chart (fig. 1) is based on the data from the Pilot Charts published by the United States Hydrographic Office. On these, the average currents have been computed for each quarter of the year and for each one-degree quadrangle for which there are sufficient data. Where the current flows in one direction for at least three of the four quarters solid arrows are used. Where the currents are less steady, broken arrows are used, and regions of great variability are indicated by crosses.

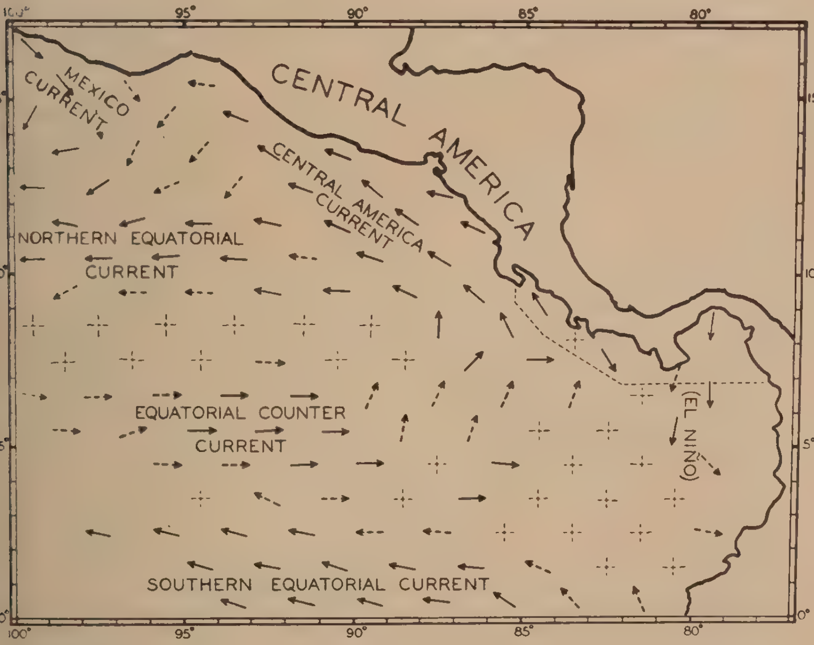


Fig. 1. Generalized pattern of surface flow in the Central American region. Crosses indicate areas of variable currents.

The southward flow along the coast of North America barely enters the chart, where it is indicated as the Mexico Current. Most of the Northern Equatorial Current in the area shown is supplied by the Counter Current, which is deflected north and west along the coast as the Central America

Current. The Peru Current is the source of the water flowing westward in the Southern Equatorial Current, and it should be noted that this extends across the equator into the Northern Hemisphere. The Equatorial Counter Current is bordered by zones of weak or indefinite flow, and the region to the south and west of the Gulf of Panama shows no permanent pattern of currents. The reason for the existence of areas of no permanent flow in the generalized chart is not that currents are lacking in the areas, but rather that they fluctuate so widely because of the annual cycle in the location of the Equatorial Currents. During the northern summer the system is displaced northward and the Southern Equatorial Current then flows in toward the Gulf of Panama and northward. During the northern winter, when the wind systems are displaced somewhat southward, the Counter Current is in large part broken down and most of the water is then carried away by the Southern Equatorial Current. The northerly wind, which at this season of the year blows across the land from the Atlantic, brings about marked upwelling in the Gulf of Panama and along the coast of Central America. The light, warm water normally present is driven southward and in exceptional years it is found along the coast of Peru where it is known as "El Niño."

In figure 2 the surface currents are shown by means of stream lines for each of the four quarters of the year. These have been constructed from the

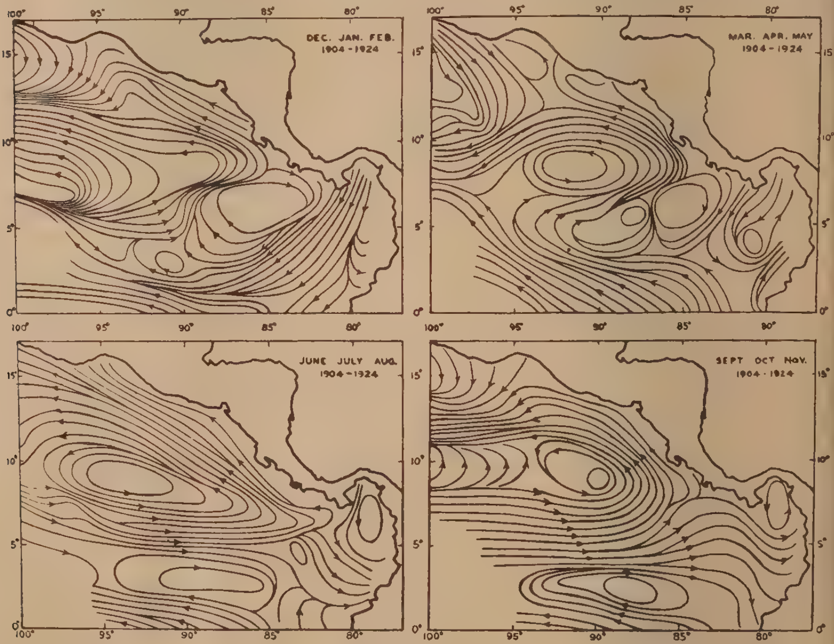
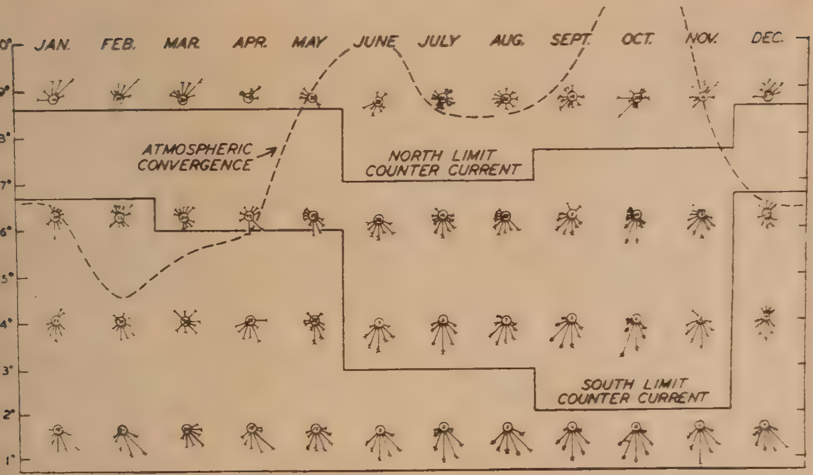


Fig. 2. Seasonal variation in the surface currents in the Central American region. Stream lines for each quarter of the year are based on the average currents for one-degree quadrangles given on the U. S. Hydrographic Office Pilot Charts.

average current for each one-degree square shown on the Pilot Charts. The extremely complicated nature of the flow during the winter is reflected in the charts for both the winter and spring quarters. Actually the marked disturbance at this season of the year is restricted to January, February, and



ig. 3. Seasonal shifts in the winds and surface currents in the Central American region tween longitudes of 85° W and 87.5° W. Dashed line represents position of the conrgence between the Trade Wind systems. Wind roses taken from U. S. Hydrographic Office ot Charts.

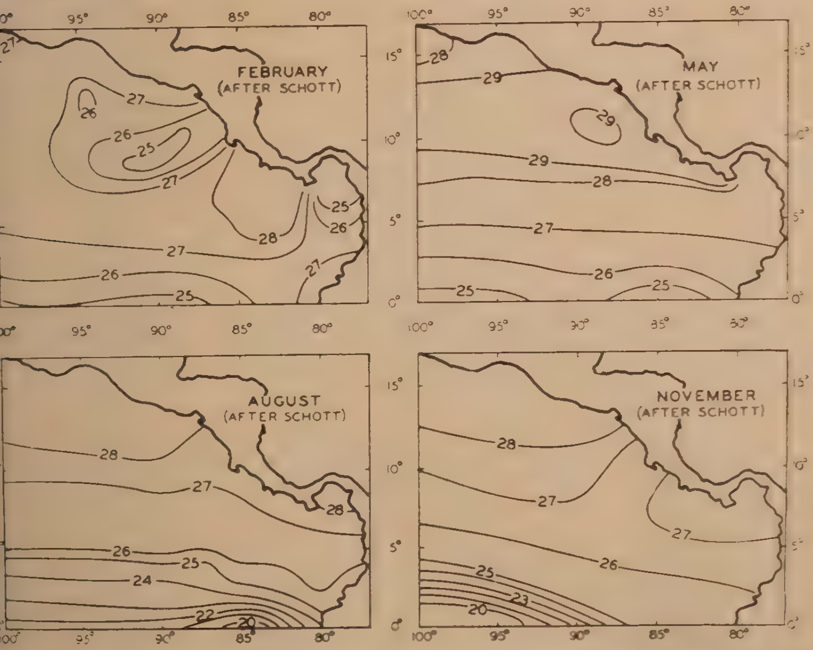

FEBRUARY (AFTER SCHOTT)
MAY (AFTER SCHOTT)
AUGUST (AFTER SCHOTT)
NOVEMBER (AFTER SCHOTT)
100°
95°
90°
85°
80°
15°
10°
5°
0°
29
28
27
26
25
24
23
22
20

Fig. 4. Seasonal changes in the surface temperatures in the Central American region. (After Schott.)

arch, as will be shown later. It is unfortunate that the quarters selected by e Hydrographic Office do not correspond to this interval. During the sumer and fall quarters the pattern of flow is much more clearly defined.

The relationship of the current system to the winds is shown in figure The wind roses were taken from the Pilot Charts for each month and for t zone between 85° and 87°5 W. The broken line represents the position the atmospheric convergence, taken from Werenskiold (1922). In the wint months the convergence has its most southerly position; and its most norther occurs in the autumn. The northern and southern limits of the Equatori Counter Current are entered for each quarter. It may be seen that t northerly winds extend nearer the equator during the winter and that at th time the Counter Current is much reduced. During the rest of the year, whe the winds are from the south and west, part at least of the easterly flow ma be due to these winds. Although this figure applies only to the band betwee 85° and 87°5 W, a similar sequence of events would be found at other long tudes.

Corresponding to the shifts in the current system there are conspicuou changes in the distribution of surface temperatures, as shown in figure which has been prepared from the charts given by Schott (1935). In Febr ary, upwelling along the Central American coast reduces the temperatur and it will be shown later that the temperatures in the Gulf of Panama a reduced much below 25° at this time of the year. The relatively cold wat of the Peru Current and of the equatorial divergence show up conspicuousl in the charts for August and November, when warm water is carried in b the Counter Current.

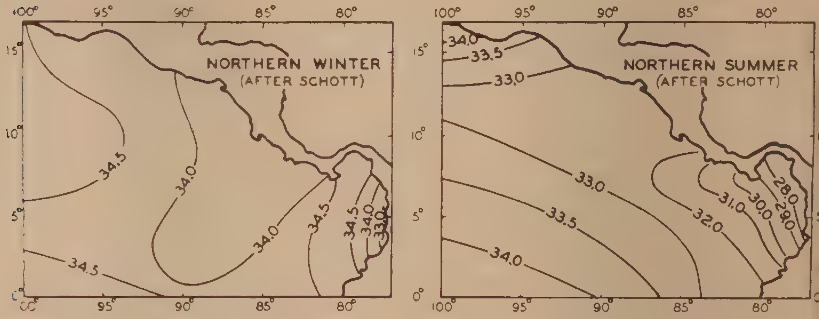


Fig. 5. Surface salinities during the northern winter and northern summer. (After Schott.)

The distribution of surface salinity during the northern winter and sur mer are shown in figure 5, prepared from charts given by Schott (1934). Du ing the northern summer there is a band of extremely low salinities extendin westward from the Gulf of Panama. These low salinities are maintained b the excessive rainfall in the equatorial calm belt, particularly near the coa of Central America where there is very heavy precipitation during this seaso of the year. During the northern winter the salinities at the surface are muc higher, for the following reasons: first, the rainfall is much less; and secon the low-salinity water has been driven south and west away from the coa by the northerly winds.

In figure 6 are shown various observations from the Gulf of Panama. Th change in the percentage of winds from the northern quadrant correspon to the variations in rainfall mentioned above. The effects of the dry, norther winds upon the conditions in the Gulf of Panama are shown by the curv representing the average monthly values of surface temperatures and se

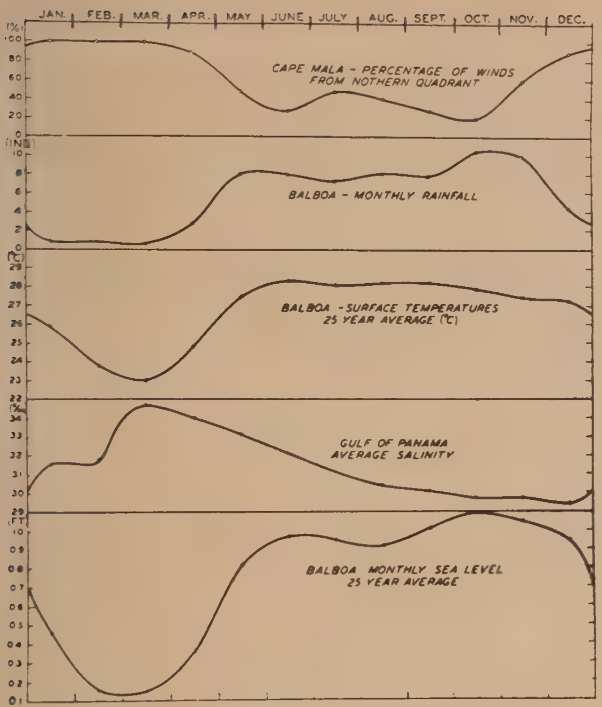


Fig. 6. Monthly values of winds, precipitation, surface water temperature, salinity, and sea level in the Gulf of Panama.

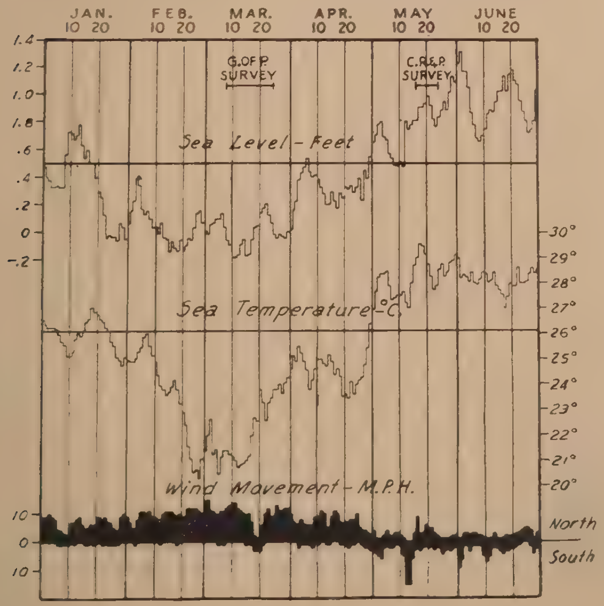


Fig. 7. Daily values of the winds, surface water temperature, and sea level at Balboa, C. Z., for the first six months of 1933.

level at Balboa, Canal Zone. Comparable data are not available for salinity but the curve for this variable represents the monthly average of a larg number of observations collected in the Gulf of Panama. With the displace ment of the surface water there is a drop in temperature and a rise in salinit which is reflected in the lowered sea level, which at this season is approxi mately one foot lower than during the summer and autumn months. If surfac

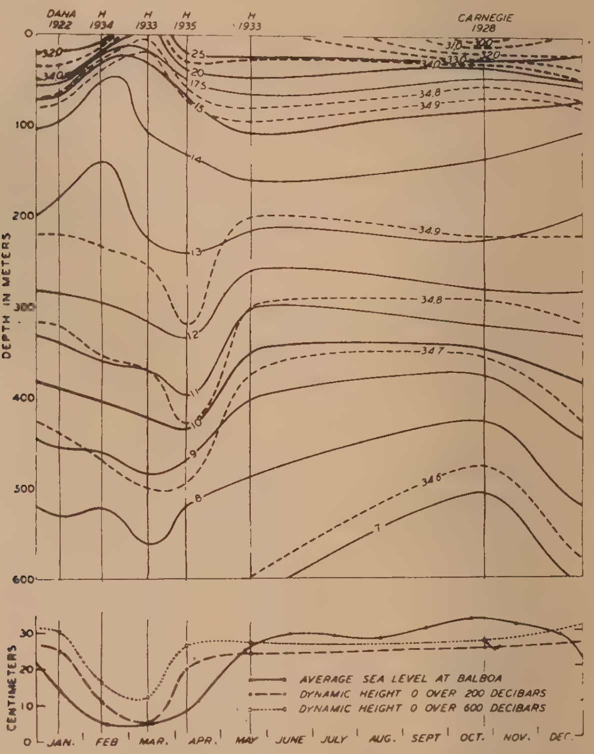


Fig. 8. Seasonal changes in the vertical distribution of temperature and salinity in the Gulf of Panama. At the bottom of the diagram are shown the curves representing the observed changes in sea level at Balboa and the dynamic height anomalies 0 over 200 decibars and 0 over 600 decibars, corresponding to the temperature and salinity distribution shown above.

temperatures are taken for individual months or weeks, they are found to b much lower during this period. Temperatures as low as 16° and salinities o nearly 35.0‰ were obtained in the Gulf of Panama during March (Fleming 1934 and 1935). That there is a very close relationship between the winds an the surface temperatures and sea level is shown in figure 7, which is base on averages for individual days in 1933.[1]

The effect of the displacement of surface water on the conditions at sub surface layers is shown in figure 8, which is based on data obtained in th Gulf of Panama at different times of the year. However, it should be note t these observations were not obtained in any single year. It can be seen m this figure that about 75 meters of water are driven out during the nter months and replaced by cold, highly saline water. In the lower part of diagram is shown the average sea level and the dynamic heights corre- nding to the temperature and salinity distribution shown in the upper t of the diagram.

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[1] The data on surface temperatures and sea level at Balboa and winds (fig. 7) were sup plied by L. T. Chapel of the Hydrographic Office of the Panama Canal Zone.

Examination of the temperature-salinity characteristics of the subsurface ter have shown them to be extremely uniform in the Central American

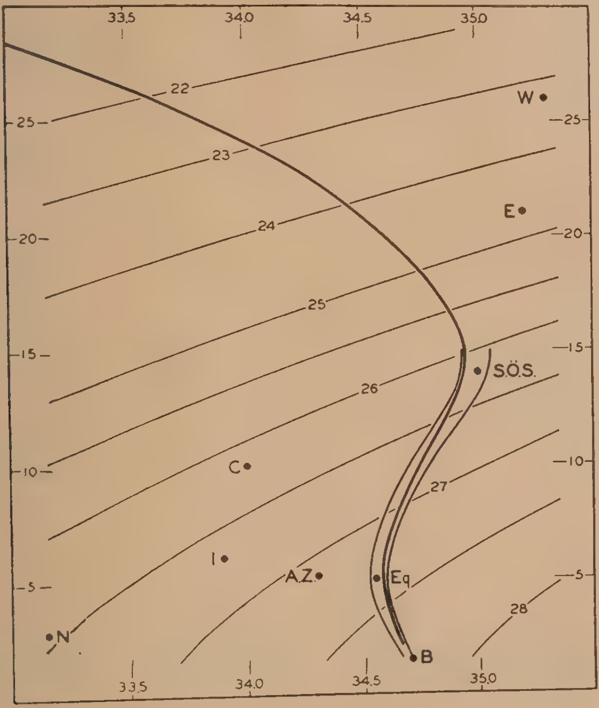

Fig. 9. Limiting curves defining the temperature-salinity relationship for the Central American region. Heavy curve is the average T-S curve for 41 stations occupied off the coast of Costa Rica and Panama. Fine lines represent ${}_t$ curves.

gion. At temperatures of less than 15°, almost all points fall between the niting curves shown in figure 9. The heavy line represents the average nperature-salinity curve, based on observations at forty-one stations off e coast of Costa Rica and Panama (Fleming, 1934). From this it may be en that the upwelling in the Gulf of Panama during the winter months re- oves the warm, low-salinity water and that conditions at the surface ap- oach the point marked *S.Ö.S.*, which has a temperature of 14° and a salin- of 35.0 ‰. During the upwelling period the quantity of this type of water creases. It is probable that this water has its origin to the south of the uator, as water of this character is found at the surface off the coast of ru (Thomsen, 1935).

During the period of upwelling, tremendous quantities of plant nutrients are brought to the surface within the Gulf of Panama and as a result there a large production of phytoplankton (Allen, 1939). Further evidence of th productiveness of this region is supplied by the observations of the *Dan* (Jespersen, 1935). Extremely large quantities of macroplankton were ob tained in this area at intermediate depths.

One of the characteristics of the subsurface levels in the Central America region is the very low dissolved oxygen content of the water, as is shown i figure 10.

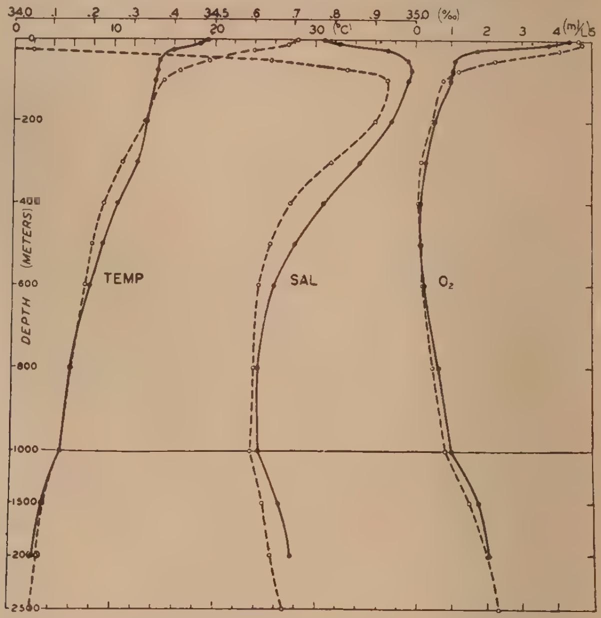

Fig. 10. Vertical distribution of temperature salinity and oxygen. Solid lines represent the average of 86 stations occupied in the Gulf of Panama in March, 1933, and dashed lines the average of 41 stations occupied off the coast of Costa Rica and Panama in May, 1933.

The Central American region is one of complex surface currents, an in addition it is extremely interesting because of the tremendous range i conditions which are encountered during the course of the year and the fac that the environment is favorable for the development of organisms in quan tities that are usually considered to be restricted to the higher latitudes.

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[Contribution from the Scripps Institution of Oceanography, New Series, No. 105.]

Contribution No. 106

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nford and San Francisco July 24 to August 12, 1939.)

THE STUDY OF SPECIES FORMATION IN CERTAIN EUCALANUS COPEPODS IN THE NORTH PACIFIC

By Martin W. Johnson

A PRELIMINARY circular sent out by the subcommittee on marine biology, question was asked: "What should be the attitude of taxonomists with gard to closely similar organisms from different geographic areas?" For zoögeographer and the taxonomist or biologist interested in relationships l racial development, the answer must be one demanding a detailed scru- y of the organism and an exact record of its systematic position and geo- uphic locality. The importance of this has long been recognized. Lohmann, his study of plankton, is quoted by Steuer (1933) as stating that it will particularly worth while to investigate the relationships that exist between velopment of subspecies and the organization of the races.

In an earlier report (Johnson, 1938) an analysis was made of the system- c position of certain Pacific offshore copepods commonly lumped more or s indiscriminately by some authors under the name *Eucalanus elongatus* thout reference to varieties established by Giesbrecht (1892). In the report ntioned, the varieties *bungii* and *inermis* were raised to the status of species d a new variety, *californicus*, was established under *E. bungii*. In the pres- t study, the importance of *E. inermis* can be discussed only briefly since ly a few specimens have been taken and from data at hand it appears to confined to a southern region not clearly connected with the northern oup, though it does show structural affinities between *E. elongatus* and *bungii*.

Mori (1937), a Japanese investigator who also recognized that *bungii* ould be considered a distinct species, gave it the specific name *giesbrechti*. owever, in keeping with the rules of taxonomic procedure, the older variety me *bungii* must be retained.

In the 1938 report mentioned above, the then known distribution of these imals along the Pacific North American coast was charted and the probable ute followed in the formation of the species was very briefly alluded to. the interim since this publication, it has been possible to extend the dis- bution chart to include also a part of the Asiatic coast, thus increasing aterially the known range of these important north Pacific copepods. This made possible through the courtesy of Dr. H. Marakawa, a pioneer in the udy of copepoda in Japan, who has supplied me with specimens collected at ° 35′ N, 163° 24′ E. and Takamochi Mori, who kindly supplied specimens om the coast of Japan, and through the recent work of the latter dealing th pelagic copepoda from the neighboring waters of Japan. This is there- re an opportune time to thank these men and to present this additional in- rmation and fuller interpretation as a report of progress which may aid further stimulating effort toward deciphering this and other similar riddles marine zoögeography.

As shown in 1938, *E. elongatus* extends along the west coast of North Amer- a from near the Galápagos Islands (Giesbrecht, 1895) to Monterey Bay. verlapping with it and extending from about 26° N (July 1939 collections) Puget Sound, with its maximum numbers along the Californian coast, is *bungii californicus*. The type variety *E. bungii bungii* extends from Cape endocino (in small numbers at least) into Alaskan waters, the Bering Sea, d even into the lower reaches of the Arctic Ocean, where it is able to repro- ıce apparently successfully during July (Johnson, 1937). It is abundant

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off the Schumagin Islands, where at times it may constitute up to 55 per cer of the larger copepods.

If *E. elongatus* be considered phylogenetically the older of the species her discussed, and if the *bungii* varieties are derived from it, it is significant tha in accordance with my previous observations: "The morphological characte separating the two forms of *E. bungii* are small yet definite and well define and it is interesting to note that morphologically *E. bungii californicus* is th one farthest removed from *E. elongatus hyalinus*[1] though geographically appears from this general survey to be the only one of the two which is i contact with that species on this coast. This raises the question whether the relationships may possibly indicate the geographical route followed in th evolution of the varieties. Has *E. bungii bungii* been derived from *E. elo* *gatus hyalinus* at its northern extension on the Asiatic coast, and has *E. bung* *californicus* later split off from this northern branch?"

Information gleaned through direct comparison of the American materi with the Asiatic samples mentioned above, and through a study of Mori locations in his taxonomic report, now show that *E. elongatus* does indee extend up the coast of Japan and that it is replaced in the northern range b *E. bungii bungii.* The material supplied by Dr. Marakawa from near Kan chatka contained only the latter species, and the material checked from th coast of Japan showed only *E. elongatus* as Mori intended. His taxonomic d scriptions and figures do not touch upon the character separating the tw varieties of *bungii,* but from so detailed a work one might justly consider th a failure to mention the point of difference would indicate a total absence *E. bungii californicus* on the Asiatic coast.

In plotting Mori's locality records for *E. bungii bungii* it is to be noted th this form was taken only in the waters north of 40° N latitude, east and sout of Hokushu where the cold waters of the Oyashio current abut upon the war Kuroshio current. The samples supplied by Marakawa were taken off the ea coast of Kamchatka, thus also in cold water, and though samples are wanti from between these locations, it is highly probable that a continuous distr bution connects these points and extends eastward to unite with the know distribution off the American coast, thus forming a continuous area includi the cold water immediately south of the Aleutian Islands. In plotting th Asiatic distribution of *E. elongatus,* the area involved extends from Formo to the offshore waters at the northern end of Honshu below 40° N latitude.

The prevailing northward-flowing oceanic current on the Japanese coa that is, the Kuroshio current, would transport *E. elongatus* northward where this stenothermic warm water animal would constantly be presse along the outposts of its dispersion, into the colder, unfavorable waters of th north. It may, however, be expected to extend eastward with the main ma of warm water (North Pacific Drift) flowing across the Pacific toward th North American coast (Shott, 1935) and thus perhaps occur in small nu bers, at least in sterile dispersion, at higher latitudes in the offshore wate along our coast where upwelled cold water is not too pronounced.

The exact origin of *E. bungii bungii* can of course not be determined wi certainty, but the common character shown in the presence of two free se ments in the abdomen proper places it nearest *E. elongatus* or *E. inermis.* far as known, however, it is now widely separated geographically from th latter species, unless there be contact in the deep cold water of the tropics subtropics; but such equatorial submergence has not been shown in this cas

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[1] This variety name established by Giesbrecht (1892) to distinguish his varieties of *elongatus* is no longer needed.

There is some difficulty in considering *E. bungii bungii* as being derived m the original stock through *E. bungii californicus* on the American coast; ucturally this would require a loss of two distinctive setae on the second is of the mandibular palp in *californicus* and then subsequently regaining se in *bungii* (see Johnson, 1928, figs. 21, 22, 23). The armature of the secl basis of the palp is distinctive even in the nauplius stages (Gibbons, 1936, 1; Johnson, 1937, p. 97). However, the intermediate relationship of *E. rmis,* through absence of lateral points on the fifth thoracic segment, may important in this connection and needs further investigation.

A most likely explanation seems to be a route of species development assoted with the great clockwise circulation in the North Pacific, in which the ntiers of the species are constantly pushed into environments more and re unfavorable to the stenothermic original stock but suitable to new strains. ner workers have shown evidences of the great importance of general oceanic culation and temperature in the formation of planktonic species. In a iew of the distribution of cold-water species, Russell (1935) considers the evailing deep-water circulation of the Atlantic as favoring formation of the ger number of antarctic and subantarctic species and deep-sea genera as ntrasted with the smaller numbers in the arctic and subarctic regions. See o Steuer, 1925, 1933.

To what extent a similar type of analysis will apply to other planktonic anils of the Pacific, we are unable to say. Our relative lack of knowledge of the agial region of the North Pacific is expressed in the following statement anslated) by Sven Ekman (1935) in his zoögeographic discussion of the rthern cold-water plankton: "On account of our rather small knowledge of nistic conditions of the North Pacific pelagial, we shall have to be satisfied h a discussion of the better known North Atlantic and of the Atlantic porn of the Arctic Ocean."

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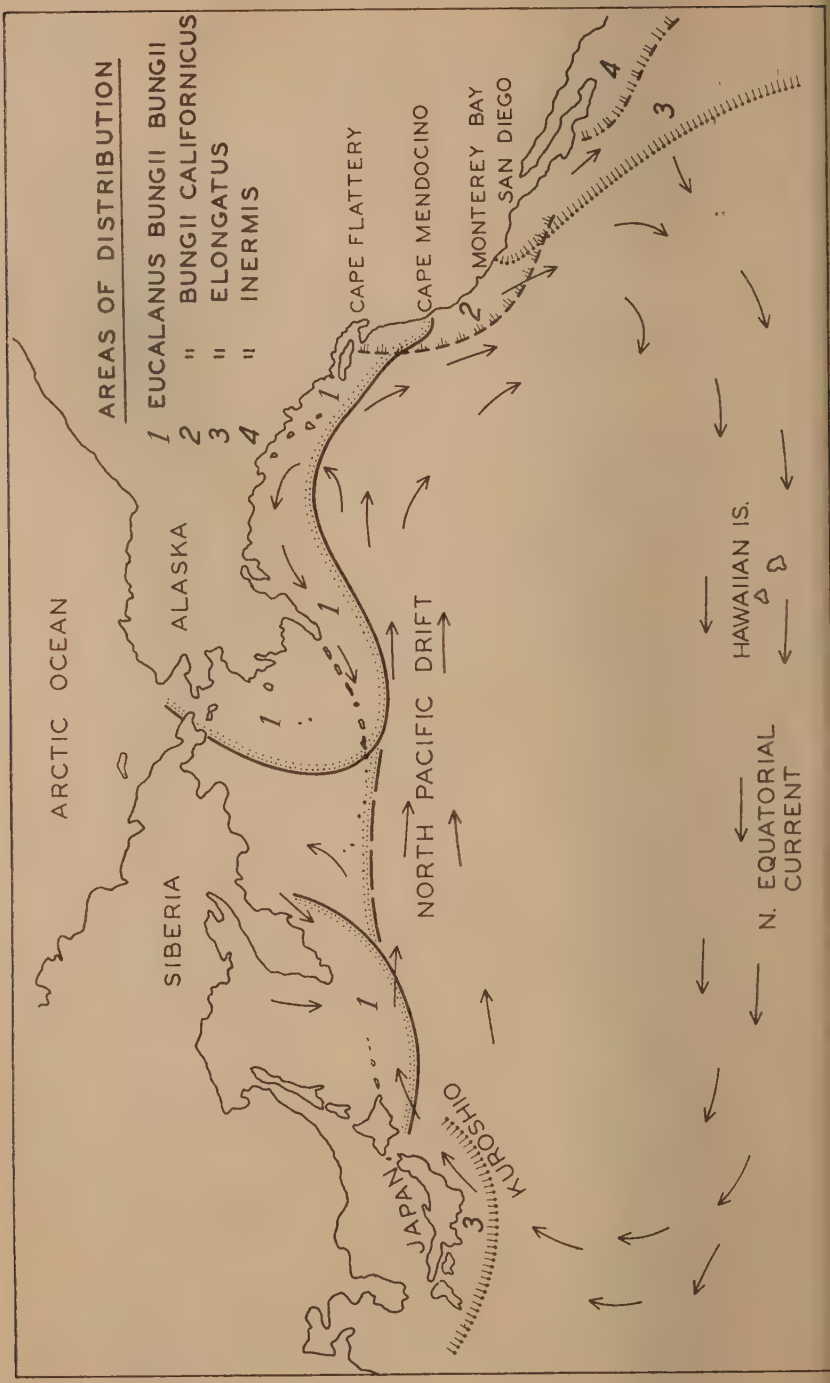
AREAS OF DISTRIBUTION
1 EUCALANUS BUNGII BUNGII
2 " BUNGII CALIFORNICUS
3 " " ELONGATUS
4 " " INERMIS
ARCTIC OCEAN
SIBERIA
ALASKA
JAPAN
KUROSHIO
CAPE FLATTERY
CAPE MENDOCINO
MONTEREY BAY
SAN DIEGO
NORTH PACIFIC DRIFT
HAWAIIAN IS.
N. EQUATORIAL CURRENT
1
1
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Contribution No. 108

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ord and San Francisco July 24 to August 12, 1939.)

A THEORETICAL DEFINITION OF PRODUCTION

By Marston C. Sargent

ce Hensen, nearly fifty years ago, began the systematic investigation of
production of the sea, a great deal has been added to the theoretical foun-
on of the investigation, while comparatively little has been accomplished
ne direction of bringing the investigation to a successful close. A further
tion to the body of theory can do no harm.

he production of a portion of the sea during a given period can be theoreti-
y defined as the number of calories of solar radiant energy converted into
nical potential energy in that portion of the sea during that period. This
nition says that a phytoplankton crop is measured not, for instance, by the
ber of cells, or their dry weight, but by their heat of combustion. Restated
her terms, production (or we can call it yield) is measured by the amount
xygen evolved by the process of photosynthesis carried on by plants. This
nition merely repeats in physical and chemical terms that the whole photo-
hetic activity of green plants and this alone constitutes the production of
sea. While most of the energy stored in the sea by plants is dissipated in
s that we might call useless or unproductive, in a humanistic sense, never-
ess this quantity of energy originally stored is the quantity we must start
when we begin to reckon the actual or possible production at some higher
gical level.

here are some small discrepancies and ambiguities in the definition of pro-
ion as given above which must be cleared up. If production (i.e., photo-
hesis) is measured by estimating oxygen evolution, an error is introduced
he fact that a small amount of oxygen is evolved by the process of nitrate
ction and sulphate reduction. The amount of oxygen evolved by nitrate
ction in green plants has been measured and found negligible as compared
the amount evolved by carbon dioxide reduction. The amount of oxygen
ved by sulphate reduction in green plants is so small that it has never
measured. Another difficulty arises from the fact that green plants carry
espiration as well as photosynthesis, and the respiration is exactly equal
nd exactly undoes a certain amount of photosynthesis. The respiration
h is supposed to occur simultaneously with photosynthesis need not con-
us, because it never appears in any measurement. However, the respira-
which occurs in plants while they are not carrying on photosynthesis,
is, at night, has the effect of making the production during a period
ng at nightfall larger than the production on the following morning.
ry night, some of the energy previously stored by photosynthesis is dissi-
d by respiration. In high latitudes and in winter this effect may be im-
ant. However, if we consider production during a minimum interval of
ours, it will be independent of the hour at which the period began.

he only excuse for this theoretical definition is that it may be of some
stance in the practical measurement of production. Up to date, three
cipal methods have been used for the practical estimation of production.
method consists of taking a census of the phytoplankton population either
or at intervals. The population may be enumerated, cell by cell, or it
be weighed, wet or dry, or it may be estimated from its content of some
stituent, such as the acetone soluble pigments. It is clear that a single
us gives no information about production, because production, by any
nition, depends on rate of change of population, which may actually be
pendent of size of population. However, by analogy with crop plants a
or a series of censuses might yield information about production. If the

population is found to be small on a given date and larger on some subseque
date, the difference might represent the amount of production between t
two dates. This would be true if the population were subject to no attrition
the interval. But if the population were not subject to attrition we would n
be interested in it. Only because the phytoplankton organisms are continual
being consumed are they of importance in the picture of production. And
long as they are continually consumed, the difference between the counts
any two days is no measure of the number produced in the interval. Besid
these, so to speak, swivel-chair objections, the methods of taking censuses ha
been subject to numerous practical criticisms. These have to do principal
with the methods of collection, the errors of estimation, the proper weighti
of samples, and the choice of stations. Most of the criticisms have been met,
can be met, in the actual collection of data for the solution of a given proble
If they are met, and if the data are interpreted in connection with informati
of a kind to be described below, the method of taking censuses becomes one
the most important tools in estimating production.

The second method used for estimating production involves the measu
ment of changes in the sea water which can be correlated with the activities
phytoplankton. For instance, increase in alkalinity during an interval h
been used as a measurement of the carbon dioxide removed by photosynthes
The decrease in dissolved phosphate has been used in estimating the increa
in phytoplankton. In principle, the difference between this method and t
first is that the quantities measured are more stable than the quantity
phytoplankton. A portion of the phytoplankton produced during a giv
period may have disappeared during the period by being eaten or by meeti
other lethal conditions, and hence never appears in a census taken at the e
of the period. However, the phosphate removed from solution by this porti
of the phytoplankton is not, in general, returned immediately to the solu
condition, but remains out of circulation for a period, perhaps as long a
month, according to experiments by Cooper (1935). If phytoplankton alwa
contains a fixed proportion of phosphorus, the quantity of soluble phospho
disappearing from the sea during certain brief intervals can be considere
satisfactory measure of the phytoplankton production during those interva
However, over long periods the regeneration of soluble phosphate impa
the accuracy of the estimation, and for any period beginning at a time wh
regeneration is already well established, changes in phosphate concentrati
may be quite independent of production. The estimation of production fr
observations on changes in the oxygen content or the alkalinity of sea wa
is similarly limited by the fact that these quantities are subject to alterati
through exchange between the water and the atmosphere.

The third method of estimating production was introduced by Gran (192
Essentially, this method consists of enclosing a representative sample of
sea and measuring the oxygen evolution in the sample during an interv
When properly controlled, this method corresponds exactly to the estimati
of production as defined in the opening paragraph. Any bottle of raw
water collected directly without the use of a net can be expected to conta
a reasonably representative population of local phytoplankton, if we assu
that in a restricted portion of the sea there are no gross inhomogeneities
the distribution of phytoplankton. Such a bottle will, in general, conta
zoöplankton, although the degree to which the zoöplankton population is r
resentative is open to question.

In a bottle filled with a pure culture of diatoms, the measured oxygen evo
tion during 24 hours is proportional to the production. If a bottle also conta

lankton, or any heterotrophic organisms, the measured oxygen evolution ss than the amount which measures production by the amount which is sumed in the respiration of the zoöplankton. The respiration of the zo- nkton depends only on the number (or mass) of these organisms present, over a period as short as 24 hours can be considered constant. Conse- ntly, if the zoöplankton can be separated from the phytoplankton by ring or otherwise and its oxygen consumption measured, this quantity can dded to the measured oxygen evolution in the bottle of mixed plankton to in the amount of oxygen actually set free by the phytoplankton in the rval. In periods of bright sunshine, and long days, the estimate obtained adding to the reading of a bottle of mixed plankton kept under natural mination for 24 hours the reading of a similar bottle kept in the dark for ours would be sufficiently accurate because the rate of plant respiration rdinarily no more than one-twentieth the maximum rate of photosynthesis.

Vhen a sample of raw sea water is confined, it is notorious that, from the ogical point of view, it soon loses many of the properties of sea water in sea. Whatever population it contained when it was first caught, is replaced, r a few days or weeks, by a new population, usually composed of species lom found in numbers in the open ocean. The basic aspect and causes of change will not concern us here, but the result is that measurements of duction as outlined above cannot be carried out over long periods. Experi- nts lasting 24 hours are not liable to large errors from this cause.

he most serious error in this method arises from the difficulty in obtaining ample of water which contains a representative zoöplankton population. w great this error is can only be determined by extensive and careful ex- imentation. It might even turn out that the method is unworkable on ount of this single difficulty.

upposing for the moment that this unhappy possibility can be avoided, measurement described gives an accurate picture of production. Compare easurement of this kind with a measurement obtained from two censuses. there are no grazing organisms present, production during the interval died will be reflected in the increase in phytoplankton population. If there many grazing organisms, there may be a very small increase in population, n in the face of considerable oxygen production, as pointed out by Harvey, per, Lebour, and Russell (1935). If there is no regeneration of phosphate, production can be measured by the disappearance of phosphate, but if ive regeneration is occurring there may be no measurable change in phos- ate concentration during an interval of active oxygen evolution. The oxygen lution alone can be considered an accurate measure of production.

Measurements essentially like the ones proposed were carried out success- ly over a period of a year by E. Steeman Nielsen (1937) at one station in ters near Copenhagen. Because the station was quickly and easily accessible vas possible to make measurements at intervals of a week. If it is desirable make an extensive series of observations over a large area, this method omes cumbersome. However, when used in conjunction with this method, method of taking censuses can give a reliable estimate of production. The e of production is clearly a function of population, and if both quantities measured at intervals (of both time and space) the production can be imated from population measurements alone, taken at smaller intervals. this combination of methods a reliable picture of production over large eas and long periods should be attainable.

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[Contribution from the Scripps Institution of Oceanography, New Series, No. 108.]

Contribution No. 109

(Reprinted from Proceedings of the Sixth Pacific Science Congress, Volume III, held at Berkeley, anford and San Francisco July 24 to August 12, 1939.)

THE GULF OF CALIFORNIA: PRELIMINARY DISCUSSION OF THE CRUISE OF THE "E. W. SCRIPPS" IN FEBRUARY AND MARCH, 1939

By H. U. SVERDRUP

ETWEEN February 13 and March 19, 1939, the *E. W. Scripps,* the research ssel of the Scripps Institution of Oceanography, occupied 53 oceanographic stations in the Gulf of California, located on a number of lines across the Gulf. The work started off Cape San Lucas and the first line of stations was run between Cape San Lucas and Mazatlán. The other lines followed in succession from south to north, except that the last two stations were worked in the Ballenas Channel between the islands Angel de la Guardia and San Lorenzo and the peninsula (see fig. 1). By means of a sonic depth finder about 2500 soundings were made at distances which on an average were less than one mile apart. At all stations temperatures were observed and water samples collected between the surface and the bottom for determination of salinity, oxygen, and occasionally other chemical characteristics. Phytoplankton samples were obtained at seven different levels between the surface and 60 meters, vertical hauls for zoöplankton were made between 200 meters and the surface, and bottom samples were procured. Between March 18 and 25, 1939, the U. S. S. *Bushnell* occupied nine oceanographic stations between Balboa, C. Z., and San Diego, California, five of which were across the entrance to the Gulf. At these stations temperatures were observed and water samples collected for determination of salinity and oxygen.

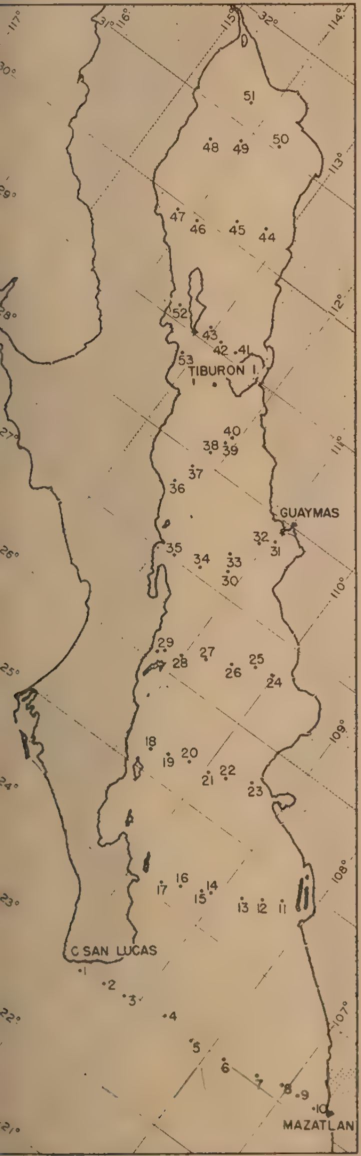

Fig. 1. Location of stations on the *E. W. ripps* cruise in the Gulf of California, ebruary 13–March 19, 1939.

In the following only the preliminary results relating to distribution of temperature, salinity, and oxygen will be discussed.

The distribution of temperature in the Gulf of California is best represented by means of a series of vertical sections across the Gulf (fig. 2). The left-hand section in the figure is the most southerly, between Cape San Lucas and Mazatlán, and the right-hand top section is the most northerly, south of Tiburon Island. The two sections shown in the bottom right-hand corner represent one from Tiburon Island

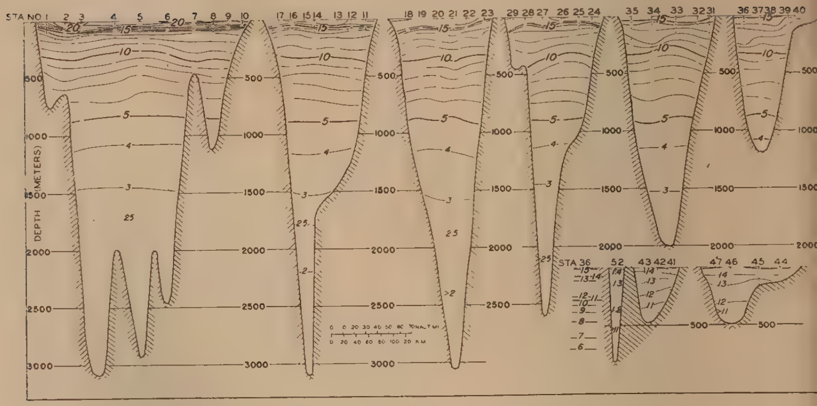

Fig. 2. Temperature profiles across the Gulf of California, *E. W. Scripps* cruise, February 13–March 19, 1939.

across Angel de la Guardia Island toward the peninsula, and one sectio across the middle part of the inner portion of the Gulf.

It is seen that in the outer portion of the Gulf, south of Tiburon Island, th surface temperature decreased toward the north. Between Cape San Luca and Mazatlán the surface temperature was above 21° at two stations, wherea off Tiburon Island the surface temperature was barely above 15°. Near th surface, evidence of upwelling is found on the eastern ends of Sections 3 an 6. Below a depth of 200 or 300 meters the temperature was very uniform an decreased regularly towards the bottom, where a temperature of less tha 2° was found below 2600 meters in the outer sections. The somewhat high temperatures in the deeper portions of Sections 3 and 4 indicate that tran verse sills are present.

In the inner portion of the Gulf the distribution of temperature wa entirely different. Even in the deepest parts a temperature of about 11° wa found. This indicates that the inner portion is separated from the outer b a sill, which probably runs about south-southeast from Tiburon Island an

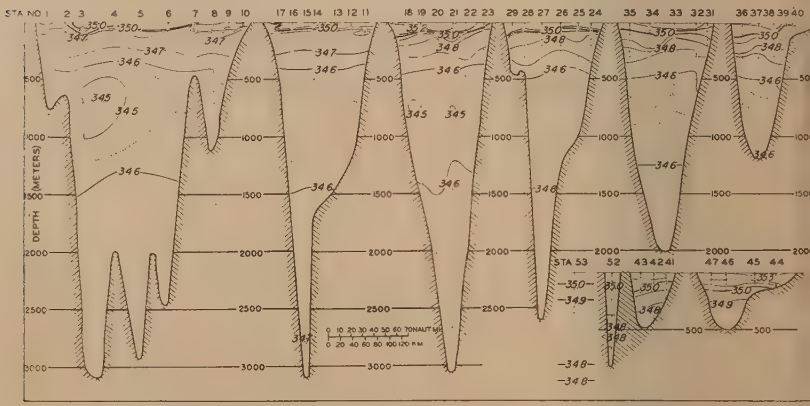

Fig. 3. Salinity profiles across the Gulf of California, *E. W. Scripps* cruise, February 13–March 19, 1939.

s a maximum depth of 200 to 250 meters. Thus, basin conditions exist in the
ner portion.

The distribution of salinity (fig. 3) showed similar features. Everywhere,
e highest salinities were found near the surface, but the maximum values
creased somewhat from the opening toward the head of the Gulf. Near the
rface the salinity curves also indicate upwelling at the eastern ends of
ctions 3 and 6. In the outer portion a layer of salinity minimum is present
depths between 500 and 1100 meters. The lowest values, slightly below
.5‰, are near the mouth of the Gulf. Farther north they are between 34.5‰
d 34.55‰. The salinity distribution also indicates that basin conditions
ist in the inner portion. From the course of the isohalines in the two north-
n sections of the outer portion it appears, however, that an exchange of
ter takes place at a depth of 150 to 200 meters. The highest surface salinity,

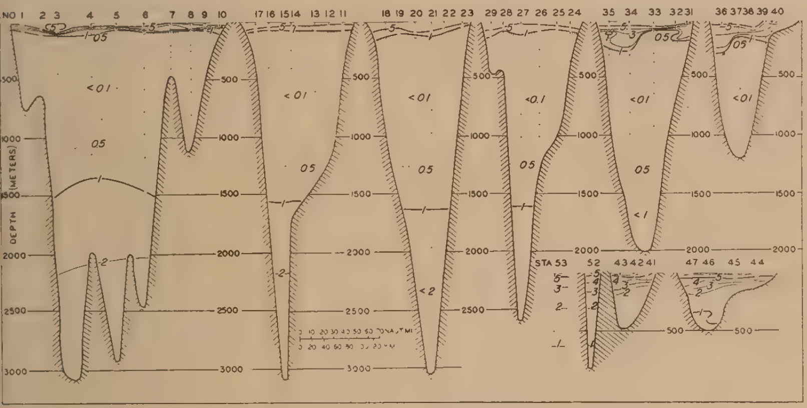

Fig. 4. Oxygen profiles across the Gulf of California, *E. W. Scripps* cruise, February 13–March 19, 1939.

.5‰, was found in the central part of the inner portion of the Gulf, but
out forty miles from the mouth of the Colorado River the salinity was
arly as high, being 35.12‰. Thus, a direct effect of the fresh water of the
lorado River is not evident, probably because of the excessive evaporation
winter.

The temperature and salinity combined clearly show that the deep water
the outer portion of the Gulf is of the type encountered over a great part
the equatorial regions in the Pacific Ocean. Water of similar character has
eviously been found off Central America and at least as far west as to longi-
de 180°. This water is characterized by a salinity minimum of approxi-
ately 34.5‰ at a temperature of about 5° and by very small amounts of
ygen at intermediate depths.

The lack of oxygen at intermediate depths is also very characteristic of the
aters of the Gulf. The oxygen sections (fig. 4) show that the oxygen con-
nt is higher than 1 ml/L in the upper 100 m. only, and that at a depth of
ss than 150 m. has decreased to 0.5 ml/L. The oxygen distribution also indi-
tes upwelling at the eastern ends of Sections 3 and 6 and shows that an
change of water takes place between the inner portion and the outer portion
the Gulf. Between about 150 meters and 900 meters the oxygen content
s been entered as being less than 0.1 ml/L and was probably less than 0.05
l/L, because the amount was too small to be accurately determined. The

deep water again contains more oxygen, up to 2.6 ml/L, as does the dee water of the central Pacific Ocean. In the inner portion of the Gulf the oxyge content is higher than in the outer, values below 1 ml/L being found onl near the bottom in some localities. The higher oxygen content indicates tha the deep water in the inner portion i formed by a mixture of water flowin over the sill and water which in winte may sink to great depths because o excessive cooling and evaporation. Thi process of vertical mixing in the inne portion and the process of upwellin account for the great fertility of th waters of the Gulf.

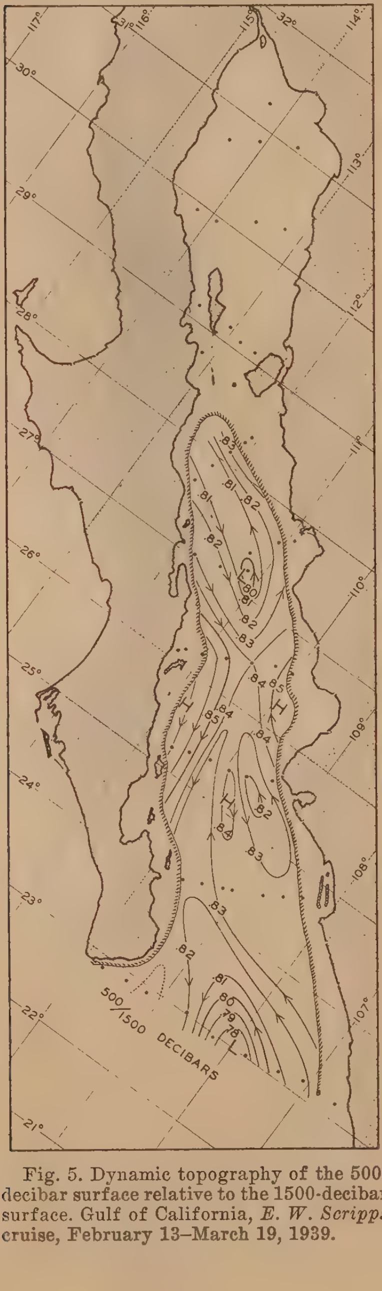

Fig. 5. Dynamic topography of the 500-decibar surface relative to the 1500-decibar surface. Gulf of California, *E. W. Scripps* cruise, February 13–March 19, 1939.

A study of the currents in the oute portions of the Gulf by means of dynamic computations led at first to ver discouraging results. The topograph of the 500-decibar relative to the 150 decibar surface (see fig. 5) does n indicate any regular exchange of wate between the Gulf and the adjacent pa of the Pacific, but shows a sequence separate highs and lows. A furthe examination of the data brought o the fact that the character of the wate below 200 m. is the same at all statio in the outer portion of the Gulf, but some stations the temperature, salinit and σ_t curves appeared to be displace upward, while at other stations the appeared to be displaced downwar The displacements are clearly seen a longitudinal section (fig. 6) based data from stations along the center li of the Gulf. To the left in the figu is shown a small map of the Gulf which are indicated the stations in t Gulf and the *Bushnell* Station 30 which have been used for constructi the section. On the central part of t figure are shown the wave-shaped curves. It should be observed that t vertical scale is highly exaggerate relative to the horizontal, the ratio b tween vertical and horizontal scal being equal to 1/800. To the right the figure are shown the profiles of series of isobaric surfaces relative the 1500-decibar surface.

The wavy character of the curv suggests the possibility that they ma be associated with a standing intern wave. The observations are not simu

eous, but at the top right-hand corner of the figure are shown the number
days elapsed between occupation of Station 5, the central station of the
thern section, and the other stations used for constructing the profile. It
evident that if the observations indicate a standing wave, the wave period
st be such that when traveling up the Gulf the vessel remained nearly in
ase with the wave. This gives immediately an indication of the possible
riod length. Station 14 appears to have been occupied near a node of the
ave, and in this case the time difference is of no importance. Station 21
pears to have been occupied shortly before the wave reached its highest
lue, and the wave period may therefore have been greater than 12.6/2,
ich means greater than 6.3 days. Station 27 was occupied after the wave
d reached its crest and the wave period may therefore have been less than
.3/2, which means less than 7.65 days. Station 30 appears to have been
ached approximately at the time when the wave at the surface reached its
west position and the wave period may therefore be approximately 19.3/3,
hich means approximately 6.4 days. Finally, Station 38 must have been
ached nearly at the time of greatest elevation. Therefore the period may be
proximately 25.3/4, which means about 6.3 days. Thus, the period may lie
tween 6.3 and 7.65 days and probably lies closer to the former value. A
riod length of about 6.6 days or 5.7×10^5 seconds appears to fit the data
ry well, but no multiple of this period length will do so. No use has been
ade of the time interval between Stations 5 and 305 because the latter also
pears to have been occupied near a node. Thus, the data can be interpreted
showing the existence of a standing internal wave with a node near the
oad opening of the Gulf and with three more nodes located in the Gulf. In
e outer portion of the Gulf the wave length appears to be of the order of
agnitude of 1000 km., but it decreases greatly toward the inner end. This
crease is undoubtedly associated with the decrease of depth. A wave length
about 1000 km. and a period of about 5.7×10^5 sec. gives a velocity of
rogress in the outer portion of 175 cm/sec. Furthermore, it is evident from
e σ_t curves that one has mainly to deal with an internal wave of the first
der having a maximum amplitude at an intermediate depth and zero
mplitude at the surface and at the bottom. From the σ_t curves one finds
at the maximum amplitude lies between 500 and 600 m. and is of the order
magnitude of nearly 100 meters.

It is possible to check these conclusions by a computation of the possible
ternal waves, using Fjeldstad's method (1933) of numerical integration.
ne difficulty is, however, encountered because the bottom of the Gulf is so
regular that what may be called the "effective" depth cannot readily be
etermined. From the observations at the deepest stations it appears that con-
nuous communication between the various depressions is present only above
000 meters. In computing the possible internal waves it has therefore been
ssumed that the depth to the bottom can be taken as 2000 meters, but it can
e added that results would not be very much altered by assuming a greater
r somewhat lesser depth. On this assumption the computation of the possible
ternal waves by Fjeldstad's method leads to the result that between Cape
an Lucas and Mazatlán the internal wave of first order has a velocity of
rogress of 175 cm/sec. and that the maximum amplitudes occur at a depth
f 775 meters. The agreement between these values and those which were
erived directly from the observations is so good that the existence of a stand-
ng internal wave during the time of the cruise cannot be doubted. A study is
n progress of the modifications of the wave length due to the decreasing
epth. It is hoped that it will be possible to find theoretically the location of
he nodes near the northern end of the Gulf.

It is evident that this internal wave completely obscures any distribution o density which may be related to the circulation of the deep water. Such circulation probably is present and consists of a slow exchange of water betwee the Gulf and the adjacent part of the Pacific, but the nature of this exchang cannot be found on the basis of our data.

It should, however, be observed that the upper isobaric surfaces slope upward from the inner part of the Gulf toward the opening of the Gulf. Thi general slope is indicated on the right-hand graph in figure 6, from whic

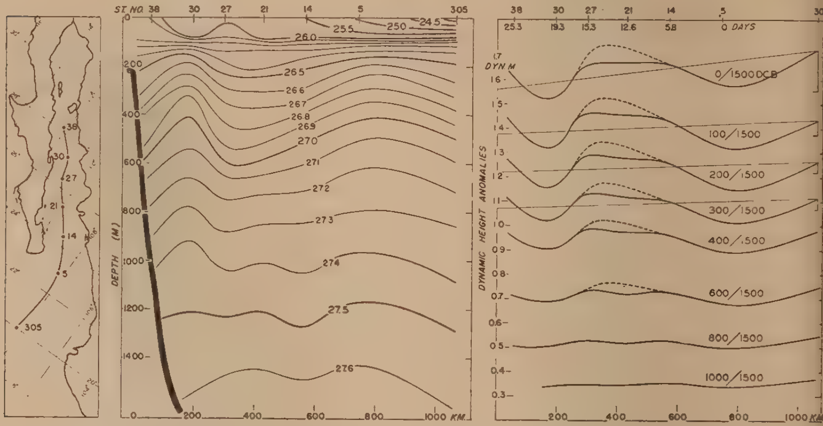

Fig. 6. Center: Longitudinal section of the Gulf of California showing distribution of σ_t according to observations at stations plotted on chart to the left. Right: Longitudinal profiles of isobaric surfaces relative to the 1500-decibar surface.

it is seen that the upward slope of the free surface is much greater than tha of the 100-decibar surface. It thus appears that a certain amount of pilin up of surface waters takes place which is probably a result of the prevailin northerly and northwesterly winds during February and March. When cruising up the Gulf, the *E. W. Scripps* encountered several strong winds blowin intermittently out of the Gulf. The pilot charts show that winds from th north and northwest prevail in the spring and that the average velocity o these winds is about 3.5 m/sec. When discussing data from the Caribbean Se (1939) I have been able to show that the average wind velocity can be computed from oceanographic data if one knows the variation of the distributio of density in the direction of the wind. The application of this method to th data from the Gulf is made difficult by the presence of the internal wave. Th selection of stations to be compared can be made in various ways, and differen combinations lead to computed wind velocities between 3.5 and 7.5 m/sec. the former value being the more probable. This value is in good agreement wit the general average wind velocity and it can therefore safely be assumed tha the piling up of the light surface waters at the entrance of the Gulf is cause by the prevailing northerly winds.

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Contribution No. 110

ACTIVITIES OF THE SCRIPPS INSTITUTION OF OCEANOGRAPHY, LA JOLLA, CALIFORNIA

By H. U. Sverdrup

Reprinted from Proceedings of the Sixth Pacific Science Congress, Volume III, held at Berkeley,
ford and San Francisco July 24 to August 12, 1939.)

ACTIVITIES OF THE SCRIPPS INSTITUTION OF OCEANOGRAPHY, LA JOLLA, CALIFORNIA

By H. U. Sverdrup

On November 13, 1936, the Institution's boat, *Scripps,* which in 1934–
had been completely overhauled and reëquipped, was lost by explosion a
fire. On April 5, 1937, Mr. R. P. Scripps bought the 104-foot schooner *Seren*
which, after remodeling, he gave to the Institution. On its transfer, its na
was changed to *E. W. Scripps.* In addition to the crew, the *E. W. Scripps* c
accommodate a scientific party of six, contains adequate laboratory space bo
on deck and below deck, and carries two winches for oceanographic work, o
provided with 2000 feet of $\frac{5}{32}$-inch wire rope and one provided with 2000 fe
of $\frac{3}{8}$-inch wire rope. The normal cruising radius under power is 2000 mil
but this can be extended by taking fuel on deck and by using the sails.

Expeditions and oceanographic data.—From June, 1935, until Novemb
1936, the *Scripps* occupied a number of oceanographic stations in the wate
near the coast of southern California between San Diego and Santa Barba
In 1937, when the Institution had no vessel at its disposal, three cruises we
made in coöperation with the California State Fisheries Laboratory, usi
their vessel, the *Bluefin.* Nearly thirty stations were occupied on each crui
along four lines running at right angles to the coast. The lines were 70 mil
apart and 160–180 miles long, the northern beginning off Port San Luis a
the southern off San Diego. In 1938 all these stations were occupied by t
E. W. Scripps on six cruises in alternate months from February to Decemb
except when, in April and October, bad weather prevented the completion
the work. On the *Bluefin* cruise, observations were made at standard interva
down to as low as 2000 meters, but on the *E. W. Scripps* cruises the work w
confined to a depth of 600 meters. On the latter cruises quantitative catches
phytoplankton were made at seven depths at all stations, and vertical hauls
zoöplankton were conducted on all cruises except the first one.

In 1933, 1934, and 1935 the U. S. S. *Hannibal* occupied a large number
oceanographic stations in the Gulf of Panama and off the coast of Pana
and Costa Rica. In 1933 R. H. Fleming of the Institution's staff spent abo
three months aboard the *Hannibal* as special observer. In 1934 the U. S.
Bushnell occupied 18 stations between Adak in the Aleutian Islands and Pea
Harbor in the Hawaiian Islands. Roger Revelle of the Institution's staff a
companied the *Bushnell.* In November, 1936, 10 stations were occupied by t
U. S. S. *Louisville* between San Pedro and Pearl Harbor. This work was und
the charge of E. G. Moberg of the Institution's staff.

In addition, the Institution has received subsurface data from various st
tions close to the American coast occupied by vessels of the United States Coa
and Geodetic Survey. About forty subsurface data were obtained by t
Valero III in 1934–35 from the area off the coast of Peru in about latitu
10° S. A large number of surface data have been submitted to the Scrip
Institution.

Physical oceanography.—The above-mentioned data have all been discuss
and published or prepared for publication except those of 1938, which a
under preparation. The *Bluefin* observations in 1937 and the observations
the *E. W. Scripps* in 1938 have shown that off the coast of southern Californ
a big eddy appears to be present during the greater part of the year. Th
eddy is especially well developed during the period of upwelling when t
offshore branch of the eddy carries cold upwelled water toward the sout
whereas the inshore branch carries water of higher temperature toward t
coast, but this inshore branch reaches only to the Channel Islands.

In order to explain the observed distribution of temperature and salinity appeared necessary to assume that an intensive quasi-horizontal mixing es place, at least down to a depth of 500 meters. This process of mixing can dealt with as a process of diffusion, by introducing a coefficient of diffusion the order of magnitude 10^8 cm^2/sec. It is probable that this mixing is mained by eddies of dimensions up to 10 or 20 km. and that the velocities may up to 20 or 30 cm/sec. Measurements of current by F. P. Shepard and Roger velle by means of a meter suspended on a tripod only 21 cm. from the bottom w that irregular currents having velocities up to 20 cm/sec. are found near bottom at depth between 50 and 800 m. The presence of such irregular curts at these depths may be considered a confirmation of the conclusions with pect to eddy motion based on distribution of temperature and salinity.

E. C. LaFond has conducted a study of the relation between coastal surface nperatures and sea level and has shown that low surface temperature corsponds to low sea level and vice versa. By means of oceanic data off the st it has been established that variations in sea level are closely associated th changes in the distribution of density of the coastal waters. Hence, the ords of sea level can be used in the study of coastal currents.

In 1936 a series of measurements of penetration of light was made by means a photocell, and in the summer of 1937 a Pettersson transparency meter s constructed and tried out. This instrument was used in August, 1938, for asuring at about 20 stations the transparency of water at different depths tween the surface and 60 meters. This work was conducted by R. T. Young, ., of Worcester Polytechnic Institute.

G. F. McEwen and his associates have continued their study of forecasting sonal air temperatures and precipitation on the basis of cycles and correlan with ocean temperatures. The public interest in these forecasts has warnted their annual publication.

Mathematical methods needed in problems of vertical flow or upwelling mbined with turbulence have been further developed. Extensive quantiive applications to data on temperature and salinity in the San Diego area ve been made. For convenience, each stage in the computation process was rried through for all the data, after the complete method had been tested a few examples, and tables were prepared to facilitate the computations.

Further developments were made in methods derived earlier of calculating velocity of horizontal currents from surface temperatures. Extensive apications of the method have been made to North Pacific Ocean data and a per presenting these results is in preparation.

As a basis for making such calculations, a study of interrelations between ocesses of radiation, convection, and evaporation near the sea surface was ade, which also provided theoretical values of the mean annual rate of evapotion at different latitudes.

An extensive W. P. A. project employing about twenty-five computers for mpiling ocean observations reported by navigators in the Pacific, sponsored the Scripps Institution about three years ago, is still in progress under the pervision of an officer of the United States Hydrographical Department. us ocean observations made since 1924 have been compiled on convenient ndard forms, from which information is transferred to punched cards for e in Washington, D. C. By special arrangement with the Hydrographic partment, the compilations on these standard forms are kept on file at the ripps Institution. These data are being averaged with respect to one-degree adrangles and months for each year, thus providing a basis for determining anges from year to year in the Japan Current off our coast, as well as the umboldt Current off the coast of South America.

Researches on smaller bodies of water, lakes or storage reservoirs, where relevent conditions are more completely observed, and processes are less complex than in the sea, are helpful in attacking problems of the sea. A paper presenting an extensive series of such observations and their interpretation in San Diego County was prepared by McEwen.

Daily observations of surface temperature and salinity have been continued at the following six stations:

Scripps Institution Pier	Latitude 32° 52′ N
Hueneme	Latitude 34° 9′ N
Pacific Grove	Latitude 36° 38′ N
North Farallon Island	Latitude 37° 42′ N
Blunt's Reef	Latitude 40° 27′ N
Balboa	Latitude 33° 36′ N

A study of the energy relations between the sea surface and the atmosphere has been completed, and by means of local observations of the vertical temperature gradient in the sea, together with the distribution of solar radiation and the amount of radiation penetrating the sea surface, the resulting evaporation from the sea has been computed. Methods for use in summarizing numerical field data have been critically examined.

Estimation of ocean currents from surface temperature distribution has been made. McEwen has devised formulas, based on considerations of surface energy relations, for estimating surface ocean currents from the distribution of temperatures. One such formula consists of a quotient of two quantities which in practice are subject to rather serious random errors which (ideally) are normally distributed in both numerator and denominator. Under the hypothesis of normal distribution, the probability distribution of values of the quotient has no standard deviation and its arithmetic mean is indeterminate, so that it has no "law of large numbers." A statistical estimate of the "true value" of such a quotient has been obtained which possesses a definite mean and satisfies a "law of large numbers" (how strongly is as yet not determined), although this estimate also has no standard deviation. These characteristics of an estimate are of importance for "least squares" treatment of data, and, for example, for estimating total transports of water over a period of time; it is hoped that this estimate will be found satisfactory.

Several applications of statistical methods to biological problems have been developed by McEwen and Gordon. Mr. Gordon has developed a new method for computing "most probable" bacterial populations from the results of successive tenfold dilutions of the sample. It is believed that tables based on the new formula will give better agreement with experimental results than Halvorson and Ziegler's tables, which are now in use.

Dr. C. E. ZoBell compared plate counts and successive dilution estimates taken from tables by Halvorson and Ziegler on the same material, with unsatisfactory results. The unsatisfactoriness is attributable to varying skewness of certain probability distributions, of which Halvorson and Ziegler's tables give the modes. Formulas have been devised for obtaining geometric means of these distributions, together with logarithmic standard deviations. It is expected that much better agreement with plate counts will thus be attained. Computation of tables to replace those of Halvorson and Ziegler wil be necessary before this can be actually tested, also for practical use. It is hoped that funds will become available to enable this to be done. Further materia is yet to be published.

Chemistry.—The work in the chemical laboratories under the charge of E. G. Moberg has for the most part dealt with routine determinations of salinity, oxygen, phosphates, and various components of the buffer mechan

n. Determinations have been made on samples regularly collected at the
stitution's pier as well as on samples obtained on the above-mentioned
uises.

Further investigations of the buffer system of the sea have been conducted
D. M. Greenberg of the University of California, Berkeley; Esther Allen,
d Messrs. R. H. Fleming and R. Revelle, and later by Mr. John Lyman. A
dy of importance in comparing the results of determinations of titratable
se or alkalinity obtained by different methods was carried out in coöperation
th P. H. Mitchell of Brown University.

Some attention has been given to the atmospheric nitrogen content of sea
ater and experiments have been made to determine nitrogen by means of
e Van Slyke blood-gas apparatus. It is believed that a method has been de-
sed that will prove practicable in laboratories on shore and possibly also on
ard ship.

A method for detecting small differences in the carbon dioxide content of
e air that may be correlated along the coast with the direction of the wind
is been developed, and a rapid and scientific method for determining arsenic
as applied to sea water by T. H. Winnick of the University of California,
erkeley.

With the assistance of the Works Progress Administration workers, numer-
us determinations of the fixed nitrogen content of bottom samples from vari-
is parts of the Pacific were made and a number of water samples were
nalyzed for organic and ammonia nitrogen and for calcium. Various methods
r determining iodine in sea water were tried by W. L. Burdick and J. Cun-
ngham. By means of one of these methods, accurate information regarding
e iodine content of a number of samples was obtained not only from the sur-
ice but also from depths down to about 1000 meters. A study of methods for
e determination of manganese and iron in sea water has also been begun.
obley D. Evans made a study of the radioactive substances in sea water, in
arine plants and animals, and in the bottom deposits off the coast of south-
n California.

Submarine geology and marine sediments.—In 1935 F. P. Shepard of the
niversity of Illinois undertook dredging for rocks from the walls of the sub-
arine canyons near La Jolla, and in 1938 this work was continued and greatly
xtended through a grant from the Geological Society of America by means
f which Mr. Shepard had the use of the *E. W. Scripps* in alternate months.
arge quantities of rocks were brought up from a number of localities, cores
f bottom sediments up to 12 feet in length were obtained, and detailed sound-
igs were made in many areas. Roger Revelle of the Institution's staff took
art in this work and conducted simultaneously laboratory studies of bottom
ediments. A large amount of mechanical analyses of sediment samples col-
cted by the *Scripps* off the southern California coast were completed. The
esults show distinct relation between the grain size of the sediments and the
pography of the bottom. Similarly, the amount of organic nitrogen in the
amples which were determined in the chemical laboratory showed distinct
lation to the configuration of the bottom. Revelle completed his discussion
f the bottom samples collected by the *Carnegie* in the course of her work in
e Pacific. Together with R. H. Fleming measurements were made of the
ariation with depth of the currents close to the bottom. It was found that in
allow water the profile of the current near the bottom corresponded closely
the velocity profile which has been established in laboratories as character-
tic for flow over a rough surface. Miss Stina Gripenberg of Helsingfors, Fin-
nd, was engaged in 1937–38 in studies of the carbon content of sediments.

Marine microbiology.—C. E. ZoBell, in charge of the bacteriological studies, has continued his work on bacteria in sea water and in bottom deposits. Fi new species have been isolated which produce ammonia from low concentr tions of urea in sea water. Observations on the influence of temperatur organic matter, pH, redox potentials, and salinity on the activities of nitrif ing and denitrifying bacteria indicate that in the sea the redox potential perhaps the most important factor. Multiplication, proteolysis, carbohydra fermentation, ammonification, and nitrification in marine bacteria have bee observed at 0° to —2° C., which indicates that bacteria are functional at tl low temperatures encountered in the deep sea.

With the assistance of D. Q. Anderson the vertical distribution and relati abundance of bacteria in marine sediments which activate a number of diffe ent physiological processes of oceanographic significance have been estimate It has been shown that bacteria have a great capacity to affect in marine bo tom deposits the O/R potentials which are of bacteriological, geological, ar chemical significance.

Assisted by Mr. Sydney Rittenberg, a microasbestos calomel half-cell h been prepared for measuring the O/R potentials of anaerobes in oval tube The device makes it possible to study the influence of bacteria upon the O/ potential and also to study the influence of O/R potentials upon the activity the bacteria.

Chitin-digesting bacteria have been found to be quite widely distributed sea water and bottom deposits. They were found in abundance in the digesti organs of squid, thereby indicating that they may aid marine animals in tl digestion of the resistant chitin which constitute the exoskeletons of mo crustacea. Lipoclastic bacteria which liberate higher fatty acids from lipi and utilize the glycerol have been demonstrated in marine materials. Thes together with those which create extremely reducing conditions, may accou for the formation of long-chain hydrocarbons found in petroleum.

Mrs. C. B. Feltham has continued the experiments on the bacterial nutritic of marine organisms. Mussels have thrived for 14 months in the dark on a di consisting exclusively of bacteria.

The importance of the presence of solid surfaces to which bacteria ca attach themselves has been examined. It is believed that the low number bacteria per unit volume in the ocean is associated with lack of surfaces p attachment. For further studies of the abundance of bacteria an improve bacteriological water sampling bottle has been perfected.

Phytoplankton.—W. E. Allen has continued the daily collections of phyt plankton from piers at Scripps Institution and Point Hueneme more tha 100 miles farther north. The microscopic work and preliminary calculatio have been completed up to 1937 and cover now a period of 18 years. A lar number of surface plankton catches have been obtained from various vesse the collections have all been examined and the results published. The surfa and subsurface collections of phytoplankton which were made on the 19 cruise of the *E. W. Scripps* have been studied and show especially that t abundance of diatoms may be as great at a distance of 180 miles from t coast as close to the coast.

Miss Easter E. Cupp has analyzed a number of phytoplankton catches means of the centrifuge method and has spent the greater part of her time preparing a taxonomic paper on plankton diatoms of the southern Californ region.

Foraminifera.—T. W. Vaughan published a number of papers on fos foraminifera. E. H. Myers has succeeded in working out the life history of local species of foraminifera known as *Patellina corrugata,* and has extend his studies to another form in which the cycle in all respects conforms to th

Patellina. M. L. Natland has continued his studies of the ecological relations
he foraminifera in the Gulf of Catalina.

Zoöplankton.—Martin W. Johnson has been engaged partly in the study of
life history of certain copepods and partly in studies of the geographic
tribution of copepods and other forms of zoöplankton. Among others, the
elopment stages of the oceanic copepods *Eucalanus elongatus* has been
npletely worked out and a report has been published on the distribution
the Pacific of the varieties of this form. The large accumulation of collec-
ns which were made by the *E. W. Scripps* in 1938 is being examined with
assistance of C. C. Davis. C. R. Monk has continued a systematic and
tributional survey of the harpacticid copepods of the Pacific coast.

Physiology of marine organisms.—D. L. Fox, in collaboration with G. W.
rks and others, has concluded a study on the habitat and food of the Cali-
nia sea mussel. Further work on the mussel has been made possible by as-
ance from the Works Progress Administration. Experiments dealing with
biochemical effects of hypotonic and hypertonic solutions of sea water
on tissues have been conducted. It has been established that the mussel
pels water through the gill chamber at an average rate of 2.5 l/hr. One of
chief lines of research has been the study of various carotenoid pigments
marine materials and marine animals, with special reference to nutrition.
rt of this study, that dealing with carotenoid pigments in marine fishes, has
n undertaken in coöperation with F. B. Sumner. The characteristic ab-
ption curves of different pigments have been established spectroscopically.

Biology of Fishes.—F. B. Sumner has continued his studies of the protec-
e value of color changes in fishes, and has experimentally established that
n-eating birds catch a much greater proportion of those fishes which do not
rmonize with the background. The work of F. B. Sumner and his collabor-
rs has, however, mainly dealt with the quantitative determination of the
ount of pigments formed in fishes which have been subjected to different
nditions with respect both to color of background and to incident light. It
s found that the amount of melanin extracted from a given lot of fishes
rs an inverse relation to the albedo of the background, probably varying
ersely as the logarithm of the albedo. Intensity of incident light also played
art in determining the production or loss of melanin, but under the degrees
illumination employed so far, the influence of this factor was small in com-
rison with that of the albedo of the background. A series of experiments
ve been commenced with a view to discovering some of the physiological
ferences between fishes which have been acclimatized to widely different
nperatures.

P. S. Barnhart has completed a monograph, *Marine Fishes of Southern*
lifornia, illustrated by 292 figures.

Studies on "fouling growth."—In 1937 coöperation was established between
e United States Navy Bureau of Construction and Repair and the Scripps
stitution in order to study the organisms which cause fouling growth on
ips' bottoms. These studies form a continuation of work which was con-
cted at the Institution over a long period of years but which had to be dis-
ntinued because of other pressing demands. Mr. W. F. Whedon, who has
en engaged by the Bureau of Construction and Repair to carry on these
dies, has been engaged mainly in examinations of the primary film formed
submerged surfaces.

Publications.—In the years 1933–1938, 265 papers have been published. A
rtial list follows, which includes only those papers which deal with general
pects of oceanographic problems or with conditions in the Pacific Ocean.

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THE SCRIPPS INSTITUTION OF OCEANOGRAPHY

by

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University of California

La Jolla

The Scripps Institution of Oceanography is a branch of the University of California which is concerned with investigating the sea, its inhabitants, its constituents, its movements and its relation to man. The organization was started nearly fifty years ago (1892) when members of the Department of Zoology of the University established a portable seaside laboratory for studying the natural history of marine organisms. It was incorporated as the Marine Biological Association of San Diego in 1903. Endowments from Miss Ellen B. and Mr. E. W. Scripps and the financial support of the state plus that from other contributing agencies have provided for the perpetuation and expansion of the work. The first permanent laboratory building was constructed in 1910 on the present 177-acre campus which is located two miles from La Jolla and sixteen miles from the center of San Diego. In 1912 it became the Scripps Institution for Biological Research of the University of California. With increasing interest in the influence of hydrographic, physical, hydrodynamical, chemical and geological conditions upon the marine environment, the name was changed to the Scripps Institution of Oceanography in 1925.

The S.I.O. now has three modern well-equipped buildings divided into 39 laboratories and offices, several smaller service buildings and a 104-foot research vessel. The latter, the E. W. SCRIPPS, is a Gloucester type auxiliary schooner having laboratory space and living accommodations for six scientists and a crew of nine. It is equipped for hydrographic work as well as for collecting and analyzing samples of water, sediments or other

Principal buildings, thousand-foot pier and research vessel of the S.I.O.

The *E. W. Scripps*, the research vessel of the Scripps Institution of Oceanography.

marine materials of interest to the botanist, bacteriologist, zoologist, biochemist, physicist, chemist or geologist. A 165 h. p. diesel engine gives it a cruising range of 2500 miles at a speed of 8 knots and it has rigging for unfurling 2000 square feet of canvas. The vessel ordinarily makes six cruises per year of two weeks duration, one of two or three months duration and a varying number of short collecting trips.

Other physical properties of the S.I.O. include a thousand foot pier on the end of which are located tide gauges, collecting devices, outboard motor boats, laboratories and a pump for circulating sea water through the aquaria. The library has more than 15,000 bound volumes, 1200 charts, 35,000 pamphlets and 300 periodicals.

The permanent resident staff is made up of thirteen scientists and about twice as many research, clerical and auxiliary assistants. It is supplemented by ten to twenty visiting investigators who come to study oceanographic subjects including problems in marine botany, zoology, ecology, biochemistry, bacteriology and geology. Experienced investigators who wish to utilize the research facilities at the S.I.O. will be welcome.

Work leading to the master's or Ph.D. degree in oceanography and certain other marine sciences is offered to qualified graduate students through a cooperative arrangement with other departments of the University and the Graduate Division. Graduate courses in physical oceanography, marine meteorology, marine geology, chemical oceanography, marine microbiology, phytoplankton, marine invertebrates, marine biochemistry and biology of fishes are offered throughout the year. Special studies in these subjects are open to advanced undergraduate students.

There is a wealth of biological material for study in the vicinity. Representatives of nearly all groups of organisms can be found either along the sandy or rocky beaches, in adjacent oceanic waters or nearby bays and estuaries. The material available for study at the S.I.O. and the opportunities afforded for making field as well as laboratory observations puts the Institution in a position to offer facilities for virtually every kind of investigation in marine biology and oceanography.

While experimental laboratory work will always be indispensable for the interpretation of field data, it is the expressed policy of Dr. H. U. Sverdrup who became the director of the S.I.O. in 1936 to extend the research program further and further towards the deep sea with emphasis upon the study of the physical, chemical and biological properties of sea water influencing the activity and distribution of plants and animals, the productivity of the sea, oceanic circulation, world weather and the relationship of oceanic conditions to the well-being of man.

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CHANGES IN THE TISSUE CHLORIDE OF THE CALIFORNIA MUSSEL IN RESPONSE TO HETEROSMOTIC ENVIRONMENTS[1]

DENIS L. FOX

(From the Scripps Institution of Oceanography, La Jolla, California)

The adult California mussel, *Mytilus californianus* Conrad is a fairly heterosmotic animal, typically marine in its environment, yet potentially euryhaline in a striking degree.

It has been shown (Fox et al., 1936) that this mollusk can live in the laboratory for long periods following sudden and continued immersion in aerated solutions of natural sea salts, varying in Cl concentration[2] from about 0.94 per cent, or approximately half that of natural sea water in the vicinity of La Jolla, to as high as 2.5 per cent, or about 34 per cent above normal values (1.86 per cent being the approximate Cl concentration of sea water at La Jolla).

Sudden exposure to concentrations of sea salts below or above these respective values proved fatal to mussels, but gradual alteration of the water in which they were immersed, over periods of several weeks, left the animals still alive in solutions diluted, on the one hand, to one-third of the normal Cl concentration (0.62 per cent Cl) or concentrated, on the other hand, to nearly twice the normal value (3.50 per cent).

The purpose of this investigation was to determine the chloride concentration in the tissues of the mussel, under the widely differing physiological conditions which must result from continued exposure to concentrations of sea salts not encountered by these animals in nature.

Extensive reviews of both older and more recent work dealing with homoiosmoticity and heterosmoticity of fishes and invertebrates have been presented in papers by Dakin (1935) and by Schlieper (1935).

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[1] Contributions from the Scripps Institution of Oceanography New Series No. 117.

[2] Cl concentration refers to the total halide ion concentration as determined in sea water analyses. The same designation, used in the present discussion, refers to the total halide concentration in parts per cent of both water and tissues, since the amounts of both Br and I are relatively very small. Concentration of "chloride" refers hereinafter to that of halide ions.

Other useful discussions of the subject are given by Adolph (1930) and by Baldwin (1937).

Experimental Methods

Diluted sea water solutions were prepared by adding distilled water to sea water, while relatively concentrated solutions were obtained by the partial evaporation of ordinary sea water without precipitating any salts.

Experimental solutions were contained in glass battery jars, each of 2½ gallon capacity. To avoid any injurious effects which might result from overcrowding, the predetermined ratio of at least one liter of water per animal was consistently adopted as a minimum. Mussels of an average length of 10 cm. (varying between 9 and 11 cm.) were employed in the great majority of experiments, although no biochemical or physiological differences of direct bearing upon the work were recognized in larger animals (12 cm.) or in somewhat smaller ones (7 to 8 cm.)

Experiments were carried out at room temperatures which varied between the approximate limits of 19° and 22° C. All solutions containing mussels were aerated continuously.

No attempts were made to adjust and maintain the pH of the various solutions, since it was found that mussels lived in piped sea water within the range of pH values encountered in the experiments. Figures representing numerous pH measurements of environmental solutions will serve as examples and are tabulated below. These measurements were made with a Beckman glass-electrode pH meter through the kindness of Mr. J. C. Hindman.

Solution	pH
(1) Sea water of normal salinity from running supply in tank containing mussels; unaerated	8.63
(2) The same; aerated	8.43
(3) The same, drained from mantle-cavity of mussel; unaerated	7.51
(4) Sea water of normal salinity from stationary supply in large jar containing mussels; unaerated	7.50
(5) Sea water, initially of normal salinity, diluted to maximum degree used in experiments, i.e. to one-third of original concentration (ca 0.62 per cent Cl); aerated	8.52
(6) Sea water, initially of normal salinity, concentrated to maximum degree used in experiments, i.e. to 54 per cent of original volume (ca 3.50 per cent Cl); aerated	8.32

Since the mussels were therefore presumed not to have been exposed to unfavorable conditions of acidity or alkalinity during the course of the experiments, it was concluded that extensive changes in the concentration of dissolved salts themselves constituted the limiting factors to life in the environment. The possibility of disturbances in " salt balance " (in the physiological sense), of experimental solutions was considered. Because calcium was believed to be the chief element prone to be precipitated as the carbonate from moderately concentrated sea water, analyses were made for dissolved calcium in sea water samples concentrated by boiling. Normally present in amounts close to 0.42 gram per liter, the dissolved calcium in a solution boiled down without precipitation to 54 per cent of its original volume (number 6 in above table) was present in the nearly theoretical amount of 0.80 gram per liter. Since this solution was the most concentrated used in any of the experiments, it was concluded that mussels were at no time exposed to solutions " unbalanced " with reference to calcium.

Experimental animals were introduced into the various solutions of altered salinity after first propping the valves apart by a few millimeters with smooth glass plugs and draining the gill chamber of sea water. Animals immersed under these conditions in sea-salt solutions varying between the approximate limits of 0.95 per cent and 2.73 per cent Cl usually relaxed their hold on the glass rod in a short time, parted their valves in a normal manner, and resumed feeding activities.

The flesh of control and experimental mussels was prepared for chloride analysis in the following way. The mussels were removed from their shells as rapidly as possible and with minimum cutting of tissues, severing only the adductors and small muscles attached to the hinge region of the shells. The flesh was blotted on absorbent paper to remove most of the adhering sea water, then rinsed briefly in 95 per cent ethyl alcohol (and reblotted) in order to remove most of the remaining sea water from body surfaces, constrict the gill capillaries, wash out sea water expressed therefrom, and coagulate the cut surfaces to allay excessive bleeding and subsequent losses of chloride-containing body fluids. The consistent adoption of this procedure resulted in a series of checks which were quite close in normal control animals, in spite of the fact that the work was done on the wet weight basis.

For chloride analysis, the method of Sunderman and Williams (1931, 1933) was followed, digesting the whole tissues in chloride-free KOH, followed by further treatment of aliquot portions with concentrated HNO_3 in the presence of an excess of dilute $AgNO_3$ solution. The excess of Ag ion was finally titrated with standard NaCNS solution in

TABLE I

Chloride concentrations in wet tissues of mussels, showing slight variations with sex, maturity and season.

Date	No.	Sex	Weight of flesh	Percentage Cl		
			grams			
8–11–37	1	♂ (much sperm)	22.88	0.99		Summer.
8–13–37	2	♂ " "	18.70	0.83		
8–13–37	3	♀ (many eggs)	14.85	0.89		
"	4	♂ (much sperm)	16.57	0.89		
"	5	♀ (many eggs)	16.50	0.82		
"	6	♀ " "	13.23	0.805	av. % Cl in whole ripe ♂ = 0.91	
"	7	♂ (much sperm)	17.59	0.83	av. % Cl in whole ripe ♀ = 0.87	
8–17–37	8	♂ (mature)	12.51	1.00	Grand av. = 0.90	
"	9	♂ "	10.025	0.965		
"	10	♀ "	8.52	1.065		
"	11	♂ "	11.50	0.81		
"	12	♀ "	10.61	0.77		
"	13	♂ (immature)	6.56	0.99		
	Gonads only	♂	16.95	0.90		
	" "	♀	15.68	0.61		
	" "	♂	15.03	0.945	av. % Cl in ripe ♂ gonad = 0.89	
	" "	♀	13.86	0.58	av. % Cl in ripe ♀ gonad = 0.57	
	" "	♂	10.24	0.82		
	" "	♀	13.61	0.52		
12–13–37	1	? (immature)	6.41	0.97		Winter.
"	2	♂ "	6.26	0.98		
"	3	? "	7.98	0.96	av. % Cl in immature animals = 0.98	
"	4	? "	8.19	0.98		
"	5	♂ "	5.96	1.005		
"	6	♂ "	5.08	0.995		
1–31–38	1	♀ (many eggs)	12.41	1.00		
"	2	♀ (spawned)	9.84	0.91		
"	3	♂ (much sperm)	16.37	0.96		
"	4	♂ " "	18.16	0.97	av. % Cl of sperm—cont'g ♂ = 0.97	
"	5	♀ (many eggs)	12.08	0.93	av. % Cl of egg—cont'g ♀ = 0.93	
"	6	♂ (much sperm)	15.69	1.01	av. % Cl of all ♀ = 0.945	
"	7	♀ (many eggs)	17.94	0.905	av. % Cl of all animals = 0.96	
"	8	♂ (much sperm)	16.49	0.945		
"	9	♀ (many eggs)	21.20	0.90		
"	10	♀ (spawned)	12.38	1.03		

the presence of ferric alum according to the well-known method of Volhard. The Volhard method was also employed for the analysis of chloride in sea-water solutions. Our experiments showed that the step involving preliminary digestion of tissues by KOH gave consistently higher values for chloride than did the ordinary " open Carius " determinations (digestion with excess concentrated HNO_3 and $AgNO_3$) employed by other workers. Sunderman and Williams (1933) report incomplete recovery of chloride when the preliminary alkaline digestion is omitted, and assign the low chloride values to interference by fatty substances.

Preliminary Analytical Survey of Normal Animals

Because parts of this research were conducted in different seasons of the year, i.e. especially in the summer and fall of 1937 and the winter of 1937-1938, it seemed desirable to compare chloride analyses of normal animals taken during August with those of animals comparable in size and weight taken in December and January. Also, because it was impossible to differentiate the sexes without sacrificing the animals' lives, and since it was conceivable that biochemical differences in sex might be reflected in the chloride content of the tissues, attention was given to the sex and relative degree of maturity throughout the same group of animals.

The data of Table I reveal that differences between the chloride content of whole bodies of summer animals and those of winter animals are of relatively small order, showing a departure of only + 0.06 per cent in the grand average, in favor of the winter animals; this difference is the same in direction and extent whether one compares ripe winter with ripe summer males, or ripe winter with ripe summer females.

Sexually immature animals exceeded in chloride content the grand average (0.93 per cent) of the combined values of mature animals of both seasons by the small departure of 0.05 per cent.

Because the demonstrated seasonal and sexual differences in chloride content fell well within the departures recorded between individual analyses, they were not regarded as significant in the experimental results. The sexual difference in chloride content appeared to be a real one, although relatively small, and for the purposes of this work, insignificant. It was doubtless due to the fact that the relatively heavy ripe ovary contained only about two-thirds as much chloride as did the male gonad.

Changes in Tissue Chloride Following Sudden Immersion in Heterosmotic Solutions of Sea Salts within the Tolerated Physiological Range of Concentrations

Reference to Figs. 1 and 2 brings out some rather consistent general facts: While mussels in nature show close agreement among one another in chloride content, wide individual variations are manifest in the rate of change in tissue chloride concentrations in both kinds of new environment. This is particularly striking in the early hours following immersion. Since mussels have been demonstrated to survive for long periods at either the hypotonic or the hypertonic concentrations here

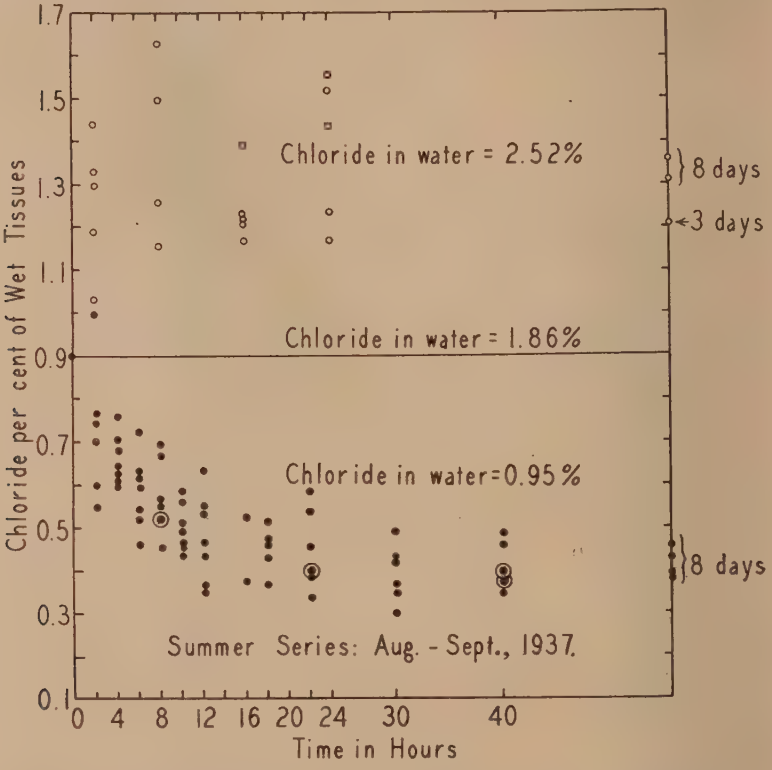

Fig. 1. Chloride analyses of whole mussel tissues following immersion of living animals for increasing time-intervals in hypotonic and hypertonic sea water within the limits of the tolerated range. Each point represents the analysis of a single animal; where two or more analytical values were identical, this is shown by concentric circles.

employed, and to eventually attain, in each group, respective chloride levels in close individual agreement, the obvious differences in the early hours are clearly due to individual variations in rate of water and salt interchange.

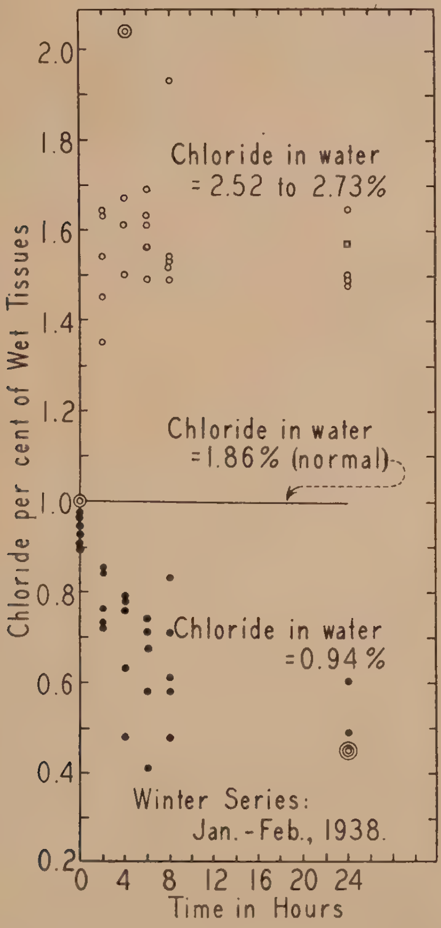

FIG. 2. Further chloride analyses, as in Fig. 1. See Fig. 1 for meaning of points and concentric circles.

While four out of five animals which remained for the whole 24-hour period in water containing 2.52 to 2.73 per cent Cl (Fig. 2) were filtering water, feeding, and voiding feces and thus appeared normal, none of the animals in the water containing 2.78 per cent Cl (Fig. 3) appeared normal even after 30 hours; they maintained a grip on the inserted glass props, failed to filter water, and gave off much mucus, thus giving several signs of physiological disturbance. A later lot, however, exposed to a solution of 2.80 per cent Cl (Table IV) did not show any effects of injury after 25 hours. These facts are taken as evidence that Cl values between 2.70 per cent and 2.80 per cent are close to the threshold of hypertonicity at which the mussels can withstand sudden immersion.

Figure 4, to which reference will be made below, reveals the close fit to a straight line *between water chlorinities tolerated by mussels after sudden immersion.* Attention is directed, for the moment, only to the portion of the graph lying between the ordinate values of 0.95 per cent Cl and 2.8 per cent Cl, illustrating the data shown in Figs. 1 and 2, and those of Table IV, when all average values of internal chloride concentrations attained by mussels in 24 to 40 hours are plotted against chloride concentrations of external water. The ratio between grams Cl per 100 grams wet mussel tissue and grams Cl per 100 ml. sea salt solution has an average value of 1 : 1.89.

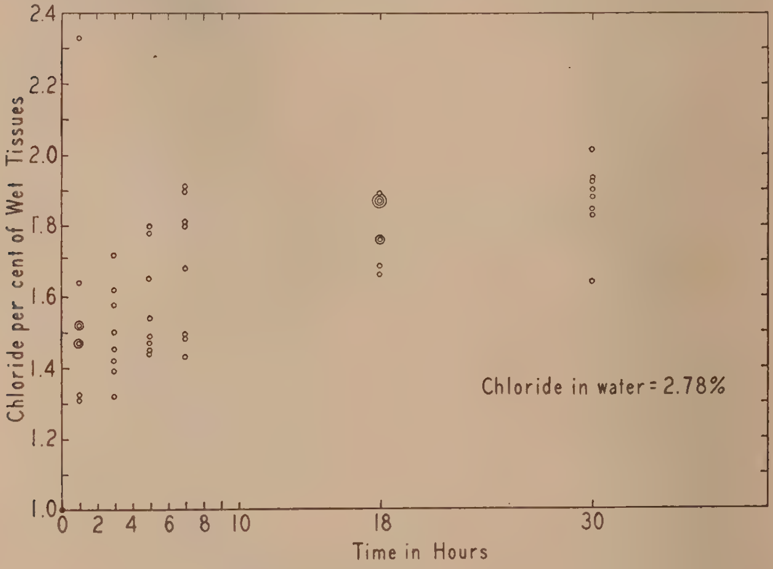

FIG. 3. Further chloride analyses, as in Figs. 1 and 2. See Fig. 1 for meaning of points and concentric circles.

The blackened point on Fig. 4 indicating the average chloride concentration in the tissues of 8 mussels maintained for 30 hours in water containing 2.78 per cent Cl was obtained from Fig. 3. While this average value lies in the vicinity of the curve, its departure is doubtless due to the fact that the animals were in poor condition (from an unknown cause), and so failed to maintain the ratio between internal and external chloride exhibited by other lots of animals at this concentration.

Specimens placed, with valves propped apart, in distilled water for 15- or 16-hour periods underwent a drop in tissue chloride to values of 0.226 per cent or even 0.112 per cent. Under these conditions animals, although not quite dead, were definitely moribund, and failed to recover when placed in running sea water.

Tolerance by the Mussel of Gradually Altered Concentrations of Sea Salts

While the immediately preceding experiments and earlier investigations seemed to define fairly well the limits of hypo- and hypertonic solutions withstood by mussels following *sudden* immersion, there were grounds for believing that *gradual* changes in the salt concentration in the animals' environment might not bring about signs of injury until greater extremes in both directions were reached.

In order to investigate this question, and to determine if possible the extremes of tissue chloride lost or gained by surviving animals, the following experiments were conducted. Two sets of mussels in separate jars of normal sea water, continuously aerated, were subjected to a gradual change in the chloride concentration of the water, one jar being diluted, the other concentrated daily by slow steps over a period of about six weeks. This gradual change was brought about in the following manner. From one jar containing about eight liters of sea water (seven mussels) some 250 ml. were withdrawn, discarded and replaced by an equal quantity of distilled water daily; from the other jar (eight mussels) the same volume of water was discarded and replaced by an equal quantity of water containing sea salts concentrated by about four-fold (i.e. Cl concentration of 7.725 per cent). These changes brought about a gradual drop in Cl from 1.86 to 0.625 per cent in the first, and a gradual rise from the same initial value to 3.48 per cent in the second solution, over the experimental period. Under these special conditions the mussels survived exposure to previously unexpected concentrations at both extremes.

Table II shows the results of chloride analyses, and a restoration of experimental animals to normal chloride levels after exposure to the gradually altered solutions during five and six-week periods.

It is assumed from the foregoing experiments that it has been possible to ascertain the approximate thresholds of tolerance of the mussel toward the osmotic effects of both hypotonic and hypertonic solutions of

Table II

Limits of tolerated changes in tissue chloride level.

Date 1937	Approximate time elapsed	Cl in hypotonic water	Cl in mussels	Cl in hypertonic water	Cl in mussels
		per cent		*per cent*	
Dec. 13, 14	5 weeks	0.84	3 animals: 0.41% 0.40 0.33 Average: 0.38%	3.09	5 animals: 2.08% 1.82 1.77 1.79 1.72 Average: 1.84%
Dec. 15	5 weeks	0.84	1 animal from same group, placed in running sea water 6 days, and analyzed: Cl = 1.1%	3.09	1 animal from same group, placed in running sea water 6 days, and analyzed: Cl = 0.935%
Dec. 20	6 weeks	0.625	0.26% (sluggish)	—	—
Dec. 21	6 weeks	0.625	0.53% (moribund) Remaining animal in this group placed in running sea water 13 days, and analyzed: Cl = 0.97%	—	—
Dec. 22	6 weeks	—	—	3.48	2 remaining animals (becoming sluggish) 2.19% 2.32 Average: 2.25%

sea salts. It seemed hardly likely, however, that individuals kept in solutions of concentrations below 0.94 per cent Cl or above 2.8 per cent Cl would survive indefinitely, since the flesh of animals in solutions beyond these respective concentrations appeared rather thin, sometimes even emaciated. Furthermore, they failed, in these respective realms of salt concentrations to maintain their constant ratio of tissue chloride to sea water chloride as illustrated in Figure 4. This graph summarizes much of the information reported above and indicates the relationship which exists between the chloride concentration in the surrounding media and that in the tissues of animals immersed therein. Each point represents the average of the analyses of a number of animals immersed in the respective solutions for 24 hours or more, save in the cases of the two lowest points on the hypotonic side, which represent analyses of two respective animals: a single survivor containing 0.26 per cent Cl and the animal which showed the highest Cl value (0.226 per cent) of the group that succumbed to immersion in distilled water (at zero abscissal value). The maintenance of a ratio of 1:1.89 between internal and external chloride is noted in the straight line between the latter concentrations of 0.94 per cent and 2.8 per cent Cl. The projection of this straight line as a dotted line beyond these values shows, when com-

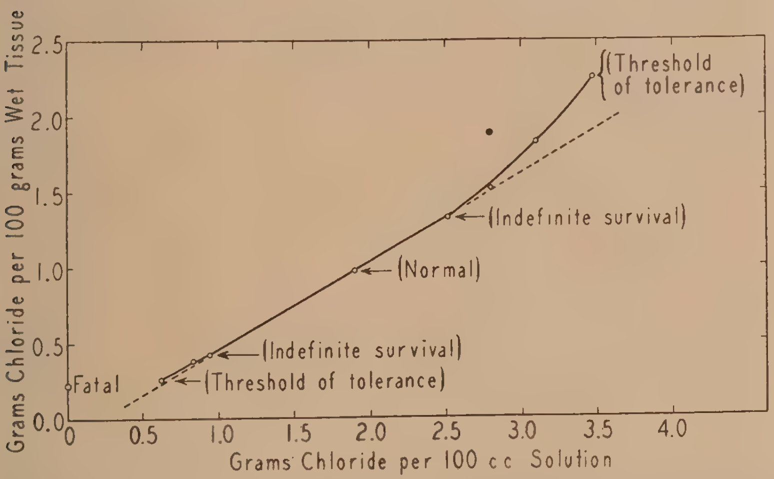

FIG. 4. Relationship between internal and external chloride, in grams Cl per 100 grams tissue vs. grams Cl per 100 ml. water respectively. Points lying between abscissal values of 0.95 and 2.8 represent results obtained after 24 hours or more following *sudden* immersion. Portions of the graph lying below and above these respective values represent the trend taken following gradual alteration of Cl concentration in the water over protracted periods, excepting wherein *distilled* water was used (see text).

pared with the actual curve, the degree of departure in the animals' maintenance of such a ratio. The final two points at each extremity of the curve represent Cl values attained by mussels after *gradual* changes in Cl concentration of the water to the corresponding values shown on the abscissa. (See Table II.)

Content of Water and Chloride in Various Tissues: Exchanges of both Water and Chloride Ions between Tissue Fluid and Environment

Since some question arose as to whether a considerable part of the observed changes in tissue Cl might be assignable to the mere presence of the medium itself in the capillary tubes of the gill structures, analyses were made of water and chloride in (1) the gills and (2) the rest of the tissues en masse, of six mussels taken directly from stock tanks of running sea water. In consistency with the experiment, tissues could not in this case be rinsed in alcohol prior to analysis (hence the slightly elevated Cl values). Table III shows the results of these analyses, and brings out the fact that the gills, as dissected for analysis, possess only a slightly higher moisture content than do the other tissues; furthermore while the chloride content of the gills was about 23 per cent higher than that of the other tissues, their relative proportion of the total wet body weight was only about 15.6 per cent, so that they were responsible

TABLE III

Water and chloride contents of gills and bodies (minus gills) of normal mussels.

Gills:	Wet weight	11.02 grams
	Dry weight	1.09 "
	H_2O	90.1%
	Cl (wet wt.)	1.32%
	Mols. Cl per liter tissue water	0.413
Bodies minus Gills:	Wet weight	59.25
	Dry weight	7.30
	H_2O	87.7%
	Cl (wet weight)	1.075%
	Mols. Cl per liter tissue water	0.345
Combined Total:	Wet weight	70.27
	Dry weight	8.39
	H_2O	88.06%
	Cl	1.11%
	Mols. Cl per liter tissue water	0.355

TABLE IV

Water and chloride contents of foot and body tissues (minus foot) of mussels immersed for 25 hours in sea water of three concentrations. N series: normal sea water, Cl = 1.86 per cent; D series: diluted sea water, Cl = 0.97 per cent; C series: concentrated sea water, Cl = 2.80 per cent.

No	Sex	Wet wt. foot	Wet wt. other tissues	Combined wet wt.	Dry wt. foot	Dry wt. other tissues	Combined dry wt.	Percentage H_2O foot	Percentage H_2O other tissues	Percentage H_2O whole body	Percentage Cl foot	Percentage Cl body	Percentage Cl whole
N 1	? immat.	0.27	10.01	10.28	0.06	1.36	1.42	77.8	86.4	86.2	.765	1.06	1.05
N 2	♂ (?)	0.255	12.83	13.09	0.06	1.72	1.78	76.5	86.6	86.4	.71	1.11	1.10
N 3	♀	0.24	10.12	10.36	0.06	1.44	1.50	75.0	85.8	85.5	.57	1.04	1.03
N 4	♂	0.20	9.72	9.92	0.05	1.36	1.41	75.0	86.0	85.8	—	1.10	—
N 5	♂	0.18	7.94	8.12	0.04	1.02	1.06	77.8	87.15	86.95	.89	1.10	1.09
N 6	♀	0.12	10.80	10.92	0.03	1.35	1.38	75.0	87.5	87.4	.66	1.10	1.10
				av.wt. = 10.45				av. = 76.1	av. = 86.6	av. = 86.4	av. = .72	av. = 1.09	av. = 1.08
D 1	♀	0.23	13.07	13.30	0.04	1.275	1.315	82.6	90.25	90.1	.32	0.51	.505
D 2	♀	0.43	15.03	15.46	0.07	1.51	1.58	83.7	89.95	89.8	.38	.48	.48
D 3	♂	0.365	13.10	13.465	0.065	1.64	1.705	82.2	87.5	87.3	.345	.50	.50
D 4	♂	0.50	15.79	16.29	0.08	1.60	1.68	84.0	89.9	89.7	.36	.51	.505
D 5	♂	0.43	14.45	14.88	0.07	1.65	1.72	83.7	88.6	88.4	.39	.465	.46
D 6	? immat.	0.255	10.78	11.035	0.04	1.11	1.15	84.3	89.7	89.6	.32	.50	.50
				av.wt. = 13.07				av. = 83.4	av. = 89.3	av. = 89.15	av. = .35	av. = .49	av. = .49
C 1	? immat.	0.19	10.96	11.15	0.05	1.58	1.63	73.7	85.6	85.4	1.15	1.60	1.59
C 2	♂	0.105	8.96	9.065	0.025	1.34	1.365	76.2	85.05	84.95	1.715	1.60	1.60
C 3	♀	0.365	8.31	8.675	0.10	1.41	1.51	72.6	83.1	82.6	0.96	1.50	1.48
C 4	♂	0.30	9.27	9.57	0.07	1.37	1.44	76.7	85.2	84.95	1.46	1.62	1.61
C 5	♂	0.405	11.77	12.175	0.10	1.63	1.73	75.3	86.15	85.8	1.15	1.42	1.41
C 6	♀	—	—	12.54	—	—	1.90	—	—	84.85		1.34	1.34
	(Foot atrophied to tiny nub)			av.wt. = 10.53				av. = 74.9	av. = 85.05	av. = 84.75	av. = 1.29	av. = 1.51	av. = 1.505

for bringing the total tissue chloride up from 1.075 per cent to 1.11 per cent, an increase of only about 3.5 per cent. Observed shifts in tissue chloride were therefore not due to environmental solution mechanically suspended in the gills.

The question of whether the change in tissue chloride concentration might be due, at least in part, to the osmotic interchange of major quantities of *water,* with or without the migration of Cl ions as well, was investigated in an experiment involving eighteen animals of the usual range of length (i.e. 92 to 110 mm.), the results of which appear in Table IV. Six mussels were immersed in ordinary sea water, six propped open in hypotonic water (" 50 per cent sea water "; 0.97 per cent Cl), and a third set of six propped open in hypertonic water wherein the Cl concentration was 2.80 per cent. After being kept in the respective, constantly aerated solutions for 25 hours, the animals were analyzed. The foot of each was severed with a sharp razor blade and analyzed separately from the other tissues, in order to determine whether such a relatively compact structure might show any considerable difference in chloride shift as compared with that of softer tissues. The dry weights of all tissues were obtained by keeping them overnight in tared containers placed in an electric oven at 105° C., then re-weighing; chloride was determined in the usual manner. In the table, the N series represent the normal control animals kept in sea water, the D series those placed in the diluted sea water, and the C series those immersed in the more concentrated solutions. Some significant trends are observed. The average water content of foot tissues and of whole bodies shows a consistent increase in the order which would have been expected from a consideration of the osmotic effects of the relative solutions, i.e., D > N > C; the relative chloride values of foot tissues or of whole bodies show the opposite order, i.e., C > N > D.

TABLE V

Weight of water and of chloride per unit weight of dry tissue; concentration of chloride per 100 grams of tissue water.

Series	Grams H_2O per gm. dry tissues			Grams Cl per gm. dry flesh			Grams Cl per 100 gm. tissue-water		
	foot	body	whole	foot	body	whole	foot	body	whole
N	3.18	6.46	6.35	0.030	0.081	0.079	0.94	1.25	1.24
D	5.025	8.34	8.22	0.021	0.046	0.045	0.42	0.55	0.55
C	2.98	5.69	5.55	0.051	0.101	0.099	1.72	1.77	1.78

The exchanges of both water and chloride ions, under the conditions of the preceding experiment, are brought out in a quantitative way in Table V, showing for each of the three series, the ratios of average water content and average chloride content, in grams per gram of dry tissue.

Furthermore, by plotting the values for Cl concentration in grams per 100 grams of tissue water, against Cl concentrations in grams per 100 ml. of sea water solutions, we arrive at the nearly linear relationships shown in Fig. 5. The foot, which contains less water, less chloride, and lower concentration of the latter, normally constitutes only about 2 per cent of the total body weight, and exerts no significant influences upon the data collected from analyses of the whole body. Nevertheless, this compact muscular tissue is observed to exchange both water and chloride with the aqueous environment in a manner similar to that of the other tissues.

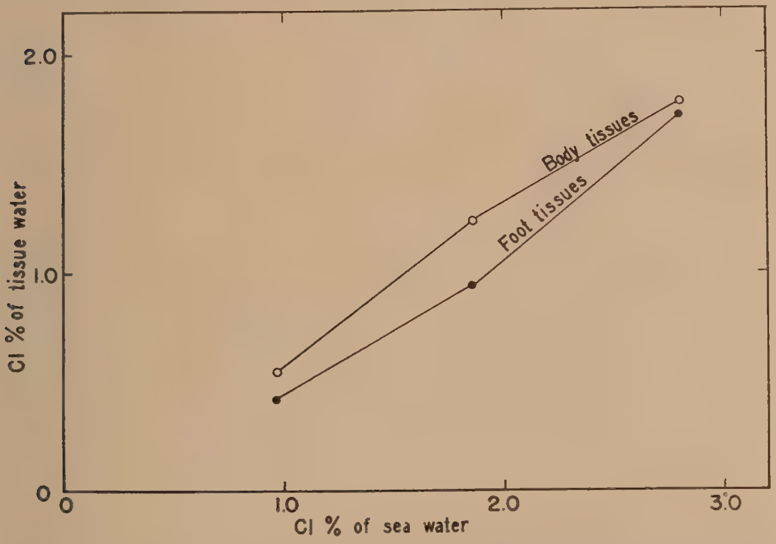

Fig. 5. Relationship between internal chloride concentrations in grams per cent of tissue water and in environmental water respectively. Sea water chlorinities lie within the range of values tolerated by mussels on sudden immersion.

Under the conditions of the above experiments, the mussel alters, throughout a physiologically wide range, the concentrations of its dissolved salts in such manner as to maintain a rather constant ratio between the Cl concentration of internal and that of external water, this ratio appearing to have an average value of the order of 1 : 1.60. The migration of both chloride and water occurs between the tissues and the solution outside.

Discussion

The ready exchange of water and chloride between the mussels' flesh and the environment may not involve any such profound changes in tissue cells themselves as might seem to be the case. The tissues of some organisms contain major quantities of the total chloride in the interstitial fluid, the cells themselves possessing the ion in very small amounts, and not readily undergoing alterations in water content or chloride concentration. This seems to be especially true in certain muscular tissues of mammals (Eggleton, Eggleton and Hamilton, 1937; Bourdillon, 1937), but some investigators are of the opinion that in other tissues (notably in frogs) considerable portion of the chloride is intracellular (Amberson, Nash, Mulder and Binns, 1938).

Since the completion of the present work, some informative results have been published by Steinbach (1940 *a, b*), who studied the content and distribution of water and electrolytes in the excised retractor muscles of certain marine invertebrates, i.e. the holothurian, *Thione briareus* and a sipunculid worm, *Phascolosoma.*

Steinbach immersed his material for a few hours in solutions containing chloride in concentrations of from 52 milli-equivalents per cent (i.e. full-strength sea-water) to nearly zero, employing isosmotic sucrose, or alternatively $NaNO_3$ solution as the sea water diluent. No hypertonic solutions were used. He obtained linear relationships throughout the experimental range of concentrations employed, the fresh *Thyone* tissue being richer in Cl (20.4 meq. Cl per cent) than that of *Phascolosoma* (9.1 meq. Cl per cent when fresh, and 16 meq. Cl per cent when soaked in sea water), and the former yielding steeper slopes of linear change. The normal water-content was very similar in both species, i.e. 75.9 per cent in *Thyone* and 78 per cent in *Phascolosoma* muscle.

The present writer immersed whole mussels for 24 hours or longer in normal, dilute, and concentrated solutions of natural sea salts within the range successfully tolerated by the animals. Linear relationships were apparent between the range of about 1.74 and 79.1 meq. Cl per cent of environmental water, when dealing with whole bodies, while such data as were collected upon the subsequently amputated foot alone revealed a nearly linear function between environmental Cl concentrations of 27.7 and 79.1 meq. Cl per cent.

It is also of interest to note that the initial concentration of Cl in Steinbach's *Thyone* muscle is virtually identical with that of the muscular foot of *Mytilus,* viz.; 20.4 and 20.3 meq. Cl per cent respectively, and that the water-contents of both are close, viz.: 75.9 per cent and 76.1 per cent. Furthermore, the Cl concentration in half-strength sea water

(Steinbach's fortified with isosmotic solutions of sucrose or $NaNO_3$, mine merely diluted) resulted in a decrease in *Thyone* muscle Cl to a value close to that determined for *Mytilus*-foot, viz.; 12 vs. 9.9 meq. Cl per cent respectively.

Steinbach's experiments led him to conclude that muscular tissues of both *Thyone* and *Phascolosoma* (classed as smooth muscle) contain sodium chloride almost exclusively in the extracellular space, that it is free to equilibrate by simple diffusion with external solutions, and that little if any can penetrate the tissue-cells themselves. He discusses the evidence in support of the conclusion that virtually all chloride is extracellular in the material studied by him, and in striated muscles of frogs and some other vertebrates as well, and that measurement of chloride content of such tissues may be employed as a relative measure of the extracellular space.

The muscular foot of *Mytilus* is observed to show osmotic behavior closely similar to that of the retractor muscles of *Thyone* and *Phascolosoma,* and must be very like the latter tissues in biochemical constitution and function.

The whole body of *Mytilus* shows a similar linear slope as does the foot tissue within the range of environmental Cl concentrations compared, but exhibits consistently higher water and Cl content. Deviations from the linear relationship between whole tissue Cl and sea water Cl which occur at extreme dilutions and extreme concentrations represent the failure of the physiological mechanism to control any longer the integrity of the chloride-free cellular space under relatively drastic conditions.

Investigations of biochemical or physiological changes in tissues of whole organisms, living successfully in controlled foreign environments, allow, in the conclusions drawn, a degree of certainty less frequently assured from data collected on isolated, surviving tissues. In the present instance, it is of much interest to note some close parallelisms between different species investigated by the respective experimental approaches.

The work reported in this paper was begun with the experimental ecological viewpoint in mind. In summarizing briefly, it is recalled that while the adult California mussel is able to adjust itself, with accompanying changes in tissue constitution, to a considerable range of salinities in the laboratory, this species, unlike *M. edulis,* is rarely if ever found in bays and estuaries, even though such waters may be considerably less diluted than were solutions which the animals have been shown experimentally to tolerate for indefinite periods.

Our findings during the course of this work suggested some experiments on the effect of dilute solutions of sea salts upon ripe sperm and eggs of this species, the process of fertilization, and subsequent development. Some preliminary experiments of this kind were accordingly carried out at the Scripps Institution by Dr. Robert T. Young, whose findings indicate that sea water diluted by more than 25 per cent may exert injurious effects upon (1) the sex products themselves, (2) incidence of fertilization, and (3) subsequent development. Doubtless the dilution of water in bays and estuaries is not the only factor responsible for the failure of *Mytilus californianus* to colonize them, but the sensitivity of eggs, sperm, and larvae to the dilute environments provides one tangible clue which should prove helpful in further attack on this and kindred problems.

Acknowledgments

I take pleasure in expressing grateful appreciation to Mr. Arthur Raymond Holland (formerly Chemist in the Federal Works Progress Administration Project No. 7039, California District No. 12), and to Mr. Hiomi Nakamura, graduate student, and to Mr. John Cunningham (Chemist, W. P. A. Oceanography Project No. 9964–D), each of whom rendered technical assistance at various stages of this investigation, including the carrying out of chloride analyses under my direction; appreciative acknowledgment is also given to other members of the same local W. P. A. project who provided valuable aid in collecting and care of animals, typing, draughting, and library service.

Summary

1. Experiments indicate that the adult mussel *Mytilus californiaus* is heterosmotic, yet potentially euryhaline to a considerable degree, although sperm, eggs and larvae are highly stenohaline toward dilution of the environment.

2. The tissue-chloride content is close to 1 per cent by wet weight, varying only slightly with season. Mature males show slightly higher chloride values than do the mature females, due to the higher chloride content of testicular tissues than of ovarian tissues.

3. Mussels can survive for indefinite periods the sudden and continued exposure of their tissues to sea water diluted by 50 per cent (Cl conc. 0.94 per cent) or water concentrated to half again its normal value (Cl conc. 2.73 per cent to 2.8 per cent). Below or above these two respective extremes, sudden immersion is fatal.

4. Within the limits of the physiologically tolerated range indicated, the concentrations of tissue chloride are adjusted to concentrations of chloride in the environment, with maintenance of an approximate value of 1 : 1.60, calculated as grams per 100 ml. of internal and external water.

5. Considerable individual differences exist in the rate of establishment of equilibrium between environmental and tissue chloride concentrations, when mussels are exposed to the indicated dilute and concentrated solutions.

6. While sudden immersion in solutions of sea salts below or above the respective limits resulted fatally, it was possible for mussels to survive in solutions considerably beyond such limits, i.e. in water diluted to as low as 0.62 per cent Cl, or concentrated to 3.48 per cent Cl, if the concentrations were altered by *gradual steps*.

7. Mussels surviving in sea water, gradually diluted to a chlorinity of 0.625 per cent Cl, underwent a fall in their tissue chloride to values of about 0.26 per cent to 0.38 per cent; animals kept in sea water gradually concentrated to a chlorinity of 3.48 per cent underwent a rise in their tissue chloride to average values of 2.25 per cent; at these respective points animals were at their threshold of tolerance and showed incipient sluggishness. Animals of such extreme chloride levels, however, recovered if placed in running sea water, and readily underwent therein a restoration of their tissue chlorides to normal values.

8. Exposure of mussels to the diluted or concentrated solutions results in migrations of both water and chloride between internal and external media.

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MARINE HARPACTICOID COPEPODS FROM CALIFORNIA*

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The marine copepods of the suborder Harpacticoida constitute a very diverse and extensive group, abundant in individuals and species. They are primarily littoral in habit, being found in every ecological niche of the littoral zone. However, in spite of their variety and abundance, this group is very poorly known on the Pacific Coast of North America. In 1884, Poppe described two new species and one new variety from the Bering Sea and North Pacific Ocean; in 1912 Baker described one new species from southern California, and in 1920 Willey described eleven species, three of them new, from northern Alaska and the Northwest Territories. Campbell (1929 and 1930) has recorded six species, including three new ones, from the Vancouver Island region, British Columbia. No other papers dealing with the marine Harpacticoid copepods of western North America are known to the writer.

The present study was begun several years ago at the suggestion of Professor S. F. Light of the Department of Zoology, University of California, Berkeley, to whom my thanks are due for his continued interest and many helpful suggestions. The work has been continued at the Scripps Institution of Oceanography under the direct supervision of Dr. Martin W. Johnson, whose intimate knowledge of the structure and biology of the copepods has been indispensable. It is a pleasure to express my indebtedness to him and also to Dr. H. U. Sverdrup, Director of the Scripps Institution, for his many courtesies during my stay at La Jolla. I also am indebted to Professor Karl Lang, of the Zoologisches Institut, Lund, Sweden, for verifying many of my determinations of species.

METHODS

Only the simplest equipment is needed for collecting Harpacticoid copepods: one or two buckets, a small silk net about ten inches in diameter, a soup strainer of coarse mesh and some bottles. In collecting the copepods from sea weeds the best method is to carry nearly a bucketful of fresh water to the collecting ground, if possible, and to energetically wash one species of sea weed at a time in it. The fresh water kills the animals and causes them to let go their holds upon the algae. The larger debris can be dipped out with the soup strainer and the copepods caught by straining the water through the plankton net. If it is not practicable to carry fresh water to the field, enough formalin may be added to a bucket of sea water to make a two per cent solution. For lack of either fresh water or formalin, the algae may be washed in sea water with good results, although some species of Harpacticoids are able to cling very tightly to the algae and are not readily washed off. Many species can be secured by merely placing some algae in a battery jar and picking the copepods up with a pipette as they come to the surface on the lighted side. One species, *Tigriopus californicus* (Baker) can be collected by merely dipping up water from high tidepools on a rocky shore. The collections are examined with a dissecting microscope as soon as possible, and the colors of the various species noted.

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* Contributions from the Scripps Institution of Oceanography, New Series, No. 119, and from the Biological Laboratory, Willamette University, New Series, No. 2.

In making preparations of the parts for detailed study, it was found that dissections could best be made in a drop of glycerin on a glass slide. Dissecting needles were made by mounting No. 12 English needles in short lengths of slightly tapered glass tubing with DeKhotinsky cement, and ground to a very fine point on a fine carborundum stone before beginning the dissection. Fast Green in 70 per cent alcohol has been used almost exclusively for staining the copepods before dissection, an hour in the stain giving a deep enough intensity for taxonomic purposes. A few drops of Bouin's fixative added to the Fast Green gives a slight yellowish cast that aids in distinguishing very fine setae in some cases. In the case of some of the larger species of copepods with heavy chitin no stain is necessary. Permanent mounts were made when needed by mounting the appendages in order in a small drop of the syrup-pectin mixture recently described by the author (Monk, 1938) (white Karo syrup, 5 cc., Certo, 5 cc., water 3–5 cc.), dried over heat, and covered with euparal and a small square cover-glass made by cutting a 22 mm. square cover-glass into nine squares with a diamond pencil. The advantage of this method is that permanent mounts can be made in a very short time, since it is not necessary to pass the animals through a series of alcohols and xylol for dehydration and clearing.

All drawings have been made with the aid of a camera lucida; those of the appendages from permanent mounts and those of the entire animal from specimens placed on a slide in the preserving fluid without a cover-glass.

Morphological Nomenclature

The body of a copepod is composed of sixteen somites, divided into three distinct regions: the head, thorax and abdomen, or the cephalosome, metasome and urosome of Sars. There is some confusion regarding the use of the latter term. Sars clearly used it to designate that part of the body posterior to the segment bearing the fifth legs, for he says (1901, pp. 1–2): "—the posterior part of the body is . . . divided into two sharply defined sections, the metasome and urosome, the former carrying the natatory legs . . . whereas the latter never carries any true appendages . . . " and in defining the Harpacticoida (1903, pp. 1–2): "The last segment of the metasome . . . has always a very movable articulation with the preceding segment, whereas it is firmly connected with the first segment of the urosome." An examination of his descriptions and figures of the Harpacticoids shows that he uses these terms consistently as stated. Wilson’s suggestion (1932, p. 9) that the part of the body behind the movable articulation be called the urosome therefore does not agree with Sars’ use of the term and is likely to cause confusion, especially since Wilson himself sometimes uses it as Sars does, e.g., in the diagnosis of the genus *Zaus*, p. 190, where he says: “urosome 4-segmented in female.” His figure shows five segments behind the movable articulation. In view of this inconsistency the term “urosome” will be used in this paper as Sars used it, i.e., to designate that part of the body posterior to the segment bearing the fifth legs.

The appendages of the Harpacticoid copepods will be designated as in the following table:

Segment	Appendage		Region
I	First antennae	(A. 1)	“Head” or Cephalosome
II	Second antennae	(A. 2)	
III	Mandible	(M.)	
IV	First maxillae	(Mx. 1)	
V	Second maxillae	(Mx. 2)	
VI	Maxilliped	(Mp.)	
VII	First legs	(P. 1)	“Thorax” or Metasome
VIII	Second legs	(P. 2)	
IX	Third legs	(P. 3)	
X	Fourth legs	(P. 4)	
XI	Fifth legs	(P. 5)	
XII	– – – – –		“Abdomen” or Urosome
XIII	– – – – –		
XIV	– – – – –		
XV	– – – – –		
XVI	Caudal rami	(Fu.)	

This is the terminology used by most investigators of the copepods, except that some still speak of one pair of maxillae and two pairs of maxillipeds. This is incorrect and should no longer be used, for various authors have shown in studies of copepod development that there are in reality two pairs of maxillae and only one pair of maxillipeds (cf. Wilson, 1932, p. 9). The abbreviations indicated in the table will be used in describing the various species.

CLASSIFICATION

Sars (1903–1911) rejected the group Podoplea of Giesbrecht, and divided the suborder Harpacticoida into a number of families. This arrangement is a very practical one and has been followed by most later workers; it has been followed in this paper with but one modification: The family *Ameiriidae* Monrad, 1927, is used, since it removes certain genera from the unwieldy family *Canthocamptidae.* Diagnoses of the genera will be given only when new species are to be added.

Description of Species

FAMILY HARPACTICIDAE

Genus *Tigriopus* Norman, 1868

Tigriopus californicus (Baker), 1912

Syn: *T. triangulus* Campbell, 1930

(Pl. I, Figs. 1–3)

This very interesting copepod occurs on rocky shores along the California coast, in small tide-pools above the high water mark, where it is subject to the splashing of the surf at high tide and to a wide variety of conditions between tides. It was described by C. F. Baker (1912) from Laguna Beach, California, but erroneously assigned to the genus *Tisbe.* The description is very inadequate, but the figures plainly show it to be a *Tigriopus*, and without doubt the same as the species described by Campbell (1930) from Vancouver Island, British Columbia. The habitat and color are the same, and the Figures of A. 1. ♂ and ♀, P. 1 ♂, and Fu. ♀ are recognizable. The Figures of P. 1 and P. 5 ♀ (Figs. 59C and 59E) are probably from an immature individual, and those of P. 3 and P. 4 (Figs. 59D and 59F) have been interchanged and are incorrect in showing certain spines as setose setae. Specimens from high tide-pools at Laguna Beach agree in all details with those from La Jolla and from the San Francisco region, and also with Campbell's description. It thus appears that there is but one species on this coast, for which the older name *californicus* must be retained.

Length, female, 0.96–1.2 mm., male, 0.94–1.10 mm.

The Pacific coast form is very similar in structure to *T. fulvus* Fischer,

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Explanation of Plate I

Tigriopus califrnoicus (Baker)
Fig. 1, P. 2♂, ×326
Fig. 2, P. 5♀, ×326
Fig. 3, P. 5♂, ×326
Zaus serratus n. sp.
Fig. 4, P. 1♀, ×326
Fig. 5, Mx. 2, ×400
Fig. 6, P. 5♀, ×326
Fig. 7, P. 5♂, ×326
Zaus latiremis n. sp.
Fig. 8, A. 1♀, ×326
Fig. 9, ♀, dorsal, ×112
Fig. 10, P. 1♀, ×400
Fig. 11, P. 5♀, ×326
Fig. 12, P. 5♂, ×326
Alteutha langi n. sp.
Fig. 13, P. 1♀, ×326
Fig. 14, A. 1♀, ×326
Fig. 15, Mp. ×326
Fig. 16, Abd. & Fu. ×326
Fig. 17, P. 5♀, ×326
Fig. 18, P. 5♂, ×326
Fig. 19, ♀, dorsal ×125

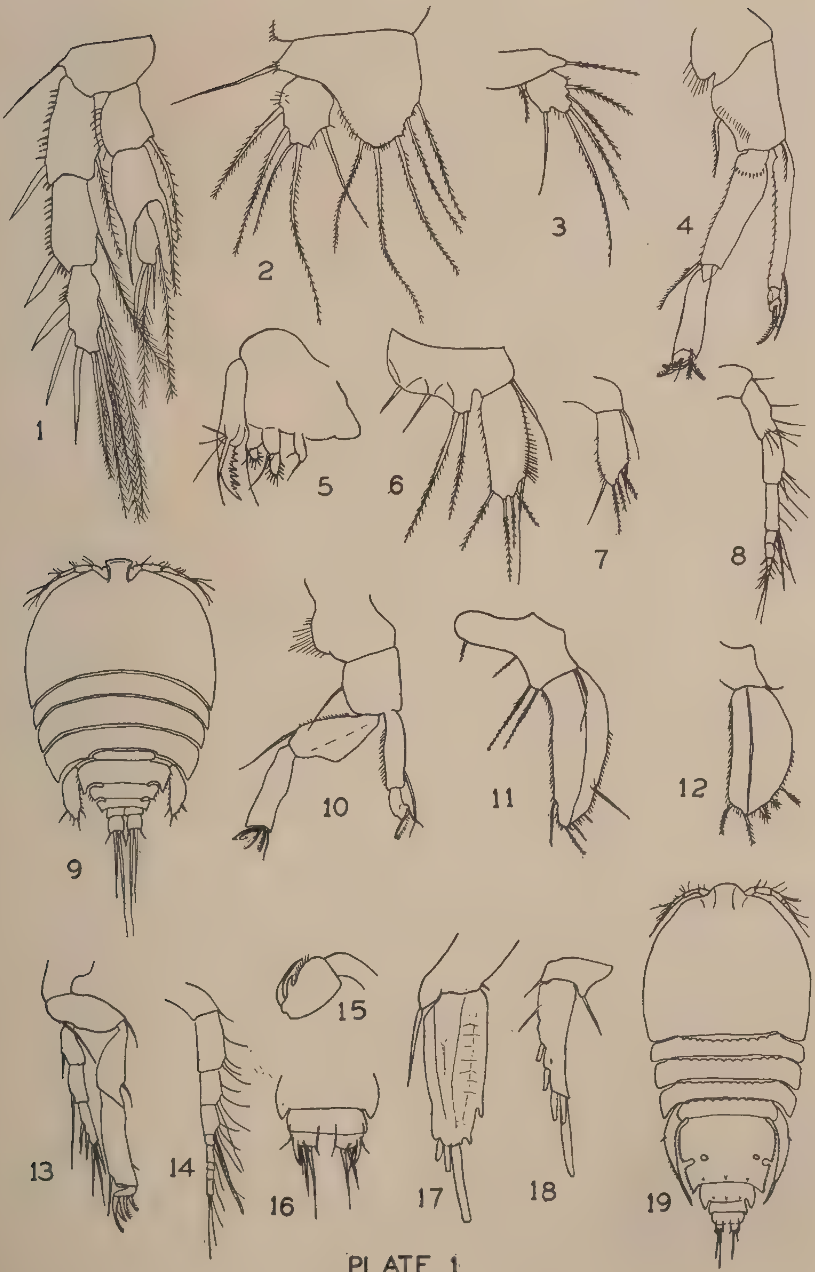
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PLATE 1

specimens of which were kindly sent to me by Dr. J. H. Fraser from the Isle of Man. The females of the two species are very nearly identical; in *californicus* the first legs appear to be stouter than in *fulvus*, the inner seta of Endo. 1, P. 1, arises nearer the middle of the segment, the proximal segment of P. 5 (Pl. I, Fig. 2) differs from that of *fulvus* in being wider, nearly triangular, and not extending beyond the end of the distal segment. In the male the endopod of P. 2 (Pl. I, Fig. 1) differs from that of *fulvus* in the shape of the last segment and in the presence of a smooth curved spine on its lower outer corner; the distal segment of P. 5 (Pl. I, Fig. 3) differs in having five setae instead of four as in *fulvus*.

The present species differs also from *T. angulatus* Lang in the form of Endo. P. 2 ♂; the inner spine on the second basis of P. 1 is shorter, and the female genital field is different, according to Dr. Lang (personal communication).

Genus *Zaus* Goodsir, 1845

Generic characters. Body short and broad, strongly depressed, segments of metasome lamellarly expanded. Rostrum short and broad. Fifth thoracic segment small, without expimeral plates. Urosome narrower than metasome, tapering sharply distally; genital segment in female partially divided, caudal rami short, setae normal. First antennae of female slender, 9-segmented, with the terminal part quite short, those of male prehensile. Second antennae with pulvinar spines on the terminal segment; outer ramus small, 2-segmented. Mouth parts similar to those of *Harpacticus*. First pair of legs with the outer ramus 2-segmented and about twice as long as the inner, which is 3-segmented, both rami provided with pectinate claws at the end. Second to fourth pairs of legs with both rami 3-segmented and nearly equal in length. Fifth legs with the proximal segment broad, distal segment well developed.

Zaus spinatus Goodsir, 1845

This cosmopolitan species is the most abundant copepod to be found on various sea weeds along the southern California coast. It has also been taken occasionally in plankton tows along the pier at the Scripps Institution. It agrees in all respects with descriptions of the European form.

Length, female, 0.55–0.75 mm., male, 0.45–0.55 mm.

*Zaus serratus** n. sp.

(Pl. I, Figs. 4–7)

Female. Larger and more flattened than *spinatus*, width more than half the length. Caudal rami slightly divergent, setae normal. A. 1 longer than in *spinatus*, the third segment distinctly longer, proportionate lengths as in the formula:

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* Referring to the peculiar character of the terminal spine of the second maxillae.

$$\frac{1-2-3-4-5-6-7-8-9}{15-19-21-12-4-4.5-3-2-2}$$

Second maxillae (Pl. I, Fig. 5) very different from those of any of the previously described species, the outer two endites of the basal segment are 2-segmented, the second segments being armed with numerous minute spines, giving them a mace-like appearance; the distal segment of the maxilla is provided with a strong toothed spine and several setae. The second segment of the exopod of P. 1 is shorter than the first and not expanded at the end, the small distal seta is nearly terminal. The first segment of the endopod of P. 1 is slender and longer than the first segment of the exopod, the two end segments are quite small, the last one bearing a curved pectinate claw and one smooth seta. P. 2–4 typical, seta formula:

Leg	Exopod Segment			Endopod Segment		
	1	2	3	1	2	3
P. 2	1	1	2.2.3	1	2	2.2.1
P. 2	1	1	3.2.3	1	1	3.2.1
P. 4	1	1	3.2.3	1	1	2.2.1

P. 5 (Pl. I, Fig. 6) with the proximal segment proportionately smaller than in *Z. spinatus*, being nearly rectangular in outline rather than square, distal segment about $2\frac{1}{2} \times 1$ and nearly as large as the proximal segment, provided with five unequal setae.

Male. Smaller than female, urosome not as broad, composed of five segments. A. 1 about as in *spinatus*, third segment not expanded distally. Mouth parts and swimming legs as in female. P. 5 (Pl. I, Fig. 7) with the distal segment almost exactly as in female, proximal segment small, without an inner expansion.

Color. Female, eye deep red, body nearly transparent, with light brown markings on A. 1, on the cephalosome, on the epimeral plates of the last free metasomal segment and on the anal segment and caudal rami. Color of male not observed.

Length. Female, 0.79–0.85 mm., male, 0.61 mm.

Occurrence. Female with the preceding species in washings from the brown alga *Eisenia arborea* Aresch. on the reef at the Scripps Institution. It has not yet been observed in washings from other sea weeds upon which *Z. spinatus* is very abundant. A few males have been found in washings from *Egregia laevigata* Setchell on the same reef, and one from a drifting specimen of the kelp *Pelagophycus porra* (Leman).

Remarks. This species may be distinguished from *Z. spinatus* by its larger size and proportionately greater breadth, by the slender endopod of P. 1, by the form of the proximal segment of P. 5, and especially by the peculiar structure of the second maxillae. It differs from *Z. caeruleus* Campbell and *Z. aurelii* Poppe in the form of the endopod of P. 1 and of the proximal segment of P. 5, as well as of the second maxillae. In the living animal the color is very distinctive.

Zaus latiremis[*] n. sp.
(Pl. I, Figs. 8–12)

Female. Proportionately much broader than the preceding species, the anterior part of the body being almost as wide as long. Urosome very short, strongly tapering, and nearly encompassed between the fifth legs. A. 1 (Pl. I, Fig. 8) with the fourth segment about as long as the third, proportionate lengths:

$$\frac{1-2-3-4-5-6-7-8-9}{6-14-13-12-4-4-2-1-2}$$

Mouth parts normal.

P. 1 (Pl. I, Fig. 10) very small, Exo. 1 with a broad medial expansion, Endo. more than half as long as Exo. P. 2–4 as in *spinatus*, but distinctly smaller. P. 5 (Pl. I, Fig. 11) very similar to that of *Z. abbreviatus* Sars; proximal segment small, provided with two short setae, widely separated, and two long setae near together. Distal segment very large, $2\frac{1}{2}\times 1$, provided with five unequal setae, one being on the inner border near the tip, and one on the outer border a little farther from the tip, the others at or near the tip.

Male. Smaller than the female and proportionately longer. A. 1 as in *spinatus*, mouth parts normal. Swimming legs as in the female. Proximal segment of P. 5 (Pl. I, Fig. 12) small, without inner expansion, distal segment 2×1, outer margin strongly rounded, armed with five unequal setae.

Color. Freshly killed specimens of both sexes were light reddish-brown on the anterior margin of the cephalosome, on the three free metasomal segments and on the fifth feet and genital segment.

Length. Female, 0.62 mm., male, 0.52 mm.

Occurrence. Six adult females, four males and one immature female were found in a collection from Laminariae dredged from thirty meters depth in Santa Catalina Channel.

Remarks. This species is very much like *Zaus abbreviatus* Sars, but may be immediately recognized by the fact that the short urosome is nearly encompassed between the large fifth feet.

FAMILY PELTIDIIDAE

Genus *Alteutha* Baird, 1845
Syn: *Carillus* & *Sterope* Goodsir
Peltidium Brady (not Philippi)

Generic characters. Body somewhat flattened, elongate oval in outline,

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[*] Referring to the broad medial expansion of the first segment of the exopod of P. 1.

lateral margins of cephalosome inflexed ventrally. Epimeral plates of the free thoracic segments well developed, those of the fifth segment much smaller and rounded. Genital segment large and expanded, succeeding segments short and tapering, epimeral plates but little extended posteriorly. Caudal rami short and broad, provided with short setae. A. 1 8–9-segmented. Mandible with biramous palp. Palp of Mx. 1 provided with a strong spine, Mx. 2 with terminal segment of moderate length, provided with a slender claw. Mp. 2- or 3-segmented, manus expanded and armed with a strong, curved claw. Swimming legs with both rami 3-segmented, exopod of first pair prehensile and longer than endopod. Fifth legs stout, elongate, and armed with stout spines.

*Alteutha langi** n. sp.
(Pl. I, Figs. 13–19)

Female. Very similar to *A. messinensis* Claus. Cephalic segment about 1/3 the total length, lateral edges inflexed ventrally. Chitin punctate, segments crenulate at the posterior margins. Dorsal surface of genital segment with three or more small conical projections in a transverse series near the posterior border. Succeeding segment also with three projections. (These are also found in *messinensis.*) Rostrum short and broad, not sharply defined. A. 1 (Pl. I, Fig. 14) as in *A. messinensis*, but slightly shorter, proportionate lengths:

$$\frac{1-\ 2-3-4-5-6-7-8-9}{10-14-9-9-3-5-2-3-5}$$

A. 2 3-segmented, exopod apparently 2-segmented. Mouth parts typical; Mp. (Pl. I, Fig. 15) with the manus subquadrate and armed with a strong curved claw.

P. 1 (Pl. I, Fig. 13) very similar to that of *messinensis*, but with Exo. slightly longer and having the inner seta of the second segment placed at the end. Last segment small, armed with three pectinate claws and one seta. P. 2–4 typical of the genus, seta formula:

Leg	Exopod Segment			Endopod Segment		
	1	2	3	1	2	3
P. 2	1	1	2.2.3	1	2	2.2.1
P. 3	1	1	3.2.3	1	2	3.2.1
P. 4	1	1	3.2.3	1	2	2.2.1

P. 5 (Pl. I, Fig. 17) elongate, proximal segment large, with a small outer, and a long inner, seta. Distal segment slightly tapering, with two small spines on the posterior border and three unequal, coarse, blunt spines at the end. Posterior border smooth, not serrate as in *messinensis*, ventral surface with irregular transverse ridges, not with rows of punctae as in that species.

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* In honor of Dr. Karl Lang of the Zoologisches Institut, Lund, Sweden.

Male. Very similar to female in size and appearance, slightly more slender. Urosome 5-segmented, genital segment with a strong spine on the posterior corner of the lateral expansion. A. 1 prehensile, 6-segmented. Swimming legs as in female. P. 5 (Pl. I, Fig. 18) more slender, posterior border provided with two coarse spines,

Length. Female, 0.68–0.80 mm., male, 0.60–0.64 mm.

Color. Eye red, posterior part of cephalic segment reddish-brown with black at posterior border and sides, extending ventrally and forward. Black also at sides of thoracic and abdominal segments, and some on basal parts of mouth parts and swimming legs. In the living animal this coloration is striking and distinctive.

Occurrence. Numerous individuals of both sexes have been found in material from the eel grass *Phyllospadix* and from several algae on the reef at the Scripps Institution. In a collection from a piece of drifting *Egregia laevigata*, taken near the end of the Institution's pier, this species constituted over 95 per cent of the copepods. It has also been found occasionally in plankton tows taken from the pier, especially when the water has been rough.

Remarks. The species here described is very similar to *Alteutha messinensis* Claus, specimens of which Prof. Monard kindly sent to Dr. Light, who has allowed me to examine them. It differs from that species chiefly in the structure of P. 5, as indicated above. It differs also from *A. interrupta* Goodsir in the structure of A. 1, which has nine instead of eight segments. The proportions of both rami of P. 1 are also somewhat different, as are the fifth legs.

Genus *Eupelte* Claus, 1860

Generic characters. Body very similar to *Alteutha*, but more flattened, more robust, and less attenuated posteriorly. Epimeral plates better developed than in that genus, those of the posterior part of the genital segment smaller. Anal segment small. Exopod of first legs with the second segment much longer than the first, endopod 2-segmented and about half as long as the exopod. All remaining legs similar to those of *Alteutha*.

Remarks. This genus was established in 1860 by Prof. Claus to receive a copepod, *E. gracilis*, from Nice, which differed from the genus *Alteutha* chiefly in having the endopod of the first legs only biarticulate. The diagnosis given in "Die Freilebenden Copepoden" (Claus, 1863) p. 143, reads: "*. . . Pes primi paris eidem Alteuthae haud dissimilis, ramus internus biarticulatus, rami externi triarticulati, articulus medianus elongatus. Pedes postici tenues.*" In the same paper Claus described two additional species, *E. bicornis*, from Naples, and *E. oblonga*, from Messina. In all of these the first endopod is only about half as long as the first exopod, and the second segment of the first exopod is at least twice as long as the first segment.

In 1912 Scott established the genus *Paralteutha* with the following brief statement: "Similar to *Alteutha* Baird, in its general form and in its cephalothoracic appendages, except that the inner ramus of the first pair of swimming feet consists of two instead of three joints; and the lateral margins of the second joint of the fifth feet are parallel, or nearly so, while the distal extremity of the joint is obliquely truncated." The genus contained only a single species, *P. typica*, from Scotia Bay, South Orkneys.

The above diagnoses do not suffice to separate *Paralteutha* from *Eupelte*, but reference to Scott's figures shows that the first endopod is nearly as long as the first exopod, and that the first and second segments of the exopod are nearly equal. (cf. Figs. 2 and 6, Plate II, of the present paper.) In *Alteutha villosa* Brady, 1910, the first legs are of the same type as in *P. typica:* this species should therefore be referred to *Paralteutha* instead of to *Eupelte* as Monard (1928, p. 319) has done. *Eupelte oblivia* A. Scott, 1909, is very different from the other species of the genus, and also differs from *Paralteutha*. The first endopod is biarticulate and short as in *Eupelte*, but the first exopod is as in *Alteuthella* Scott, 1909, with a single claw on the small third segment. The fifth legs also differ from those of the other species of *Eupelte*, as well as from those of *Paralteutha*.

Eupelte setacauda n. sp.
(Pl. II, Figs. 1–4)

Female. Body oblong, slightly narrowing behind, chitin thick, punctate. Rostrum large, truncated, and not defined at the base. Cephalic segment nearly half the total length; urosome 4-segmented. Epimeral plates of metasome extended, genital expansion very large, epimeral plates of next two segments well developed, directed backwards. Anal segment very small, without lateral expansions. Caudal rami (Pl. II, Fig. 4) subquadrate, having near the median border a stout, spine-like seta that terminates in a long slender filament, three small seta near it, a stout seta near the middle of the outer margin and two slender setae on the dorsal surface. The long filament of the large terminal seta is very easily broken off and is missing from most specimens. A. 1 (Pl. II, Fig. 1) 9-segmented, shorter than in *Alteutha*, proportionate lengths:

$$\frac{1-\ 2-3-4-5-6-7-8-9}{9-10-9-6-3-2-2-1-3}$$

A. 2 3-segmented, exopod 2-segmented, with four setae. Mouth parts as in *Alteutha*. Mp. 3-segmented, manus elongate, inner border with fine spinules; terminal claw strong and curved.

P. 1 (Pl. II, Fig. 2) with Endo, about half as long as Exo., both segments ciliated on the outer margin. Last segment of Exo. small, provided with four unequal pectinate claws and one smooth seta. P. 2–4 with both rami triarticulate and nearly equal; seta formula:

Leg	Exopod Segment			Endopod Segment		
	1	2	3	1	2	3
P. 2	0	1	2.2.3	1	2	2.2.1
P. 3	0	1	3.2.3	1	2	2.2.1
P. 4	0	1	3.2.3	1	2	2.2.1

P. 5 (Pl. II, Fig. 3) slender, with the proximal segment about two-thirds as long as the distal segment; inner expansion very small, armed with two long plumose setae and two smooth spines. Distal segment 3×1, with three stout setose spines at the tip and two smaller ones on the outer margin, inner margin with minute spinules.

Male. Slightly smaller than the female, urosome 5-segmented, anal segment small. Fourth segment of A. 1 much enlarged. Caudal rami with five unequal setae. P. 5 smaller than in the female; proximal segment without inner expansion, distal segment 2×1, with only three unequal spines.

Length, female, 0.73–0.75 mm., male, 0.70 mm.

Color. Light brown, with deep red eye.

Occurrence. A number of specimens of both sexes were found in washings from various sea weeds at Bird Rock, La Jolla, and at the Scripps Institution.

Remarks. This species may readily be distinguished from *Alteutha* by its larger size and more robust form, and from the previously described species of *Eupelte* by the presence of an inner expansion on the proximal segment of P. 5. It is very similar to *E. oblonga* Claus, from which it may be distinguished by the shape of the manus of the maxilliped, and by the fifth legs.

EXPLANATION OF PLATE II

Eupelte setacauda n. sp.
FIG. 1, A. 1 ♀, ×326
FIG. 2, P. 1 ♀, ×326
FIG. 3, P. 5 ♀, ×326
FIG. 4, Furca, ♀, ×326
Paralteutha simile n. sp.
FIG. 5, A. 1 ♀, ×326
FIG. 6, P. 1 ♀, ×250
FIG. 7, Mp. ×250
FIG. 8, ♀, dorsal, ×88
FIG. 9, P. 4 ♀, ×250
FIG. 10, P. 5 ♀, ×250
FIG. 11, Furca, ×326

Ameira longipes Boeck
FIG. 12, P. 5 ♀, ×326
FIG. 13, P. 1 ♀, ×326
Diosaccus spinatus Campbell
FIG. 14, P. 5 ♀, ×326
Scutellidium arthuri Poppe
FIG. 15, P. 1 ♀, ×326
FIG. 16, P. 2 ♀, ×326
FIG. 17, Mp. ×326
FIG. 18, P. 5 ♀, ×326
FIG. 19, P. 5 ♂, ×400
Scutellidium purpurocincta n. sp.
FIG. 20, A. 1 ♀, ×326

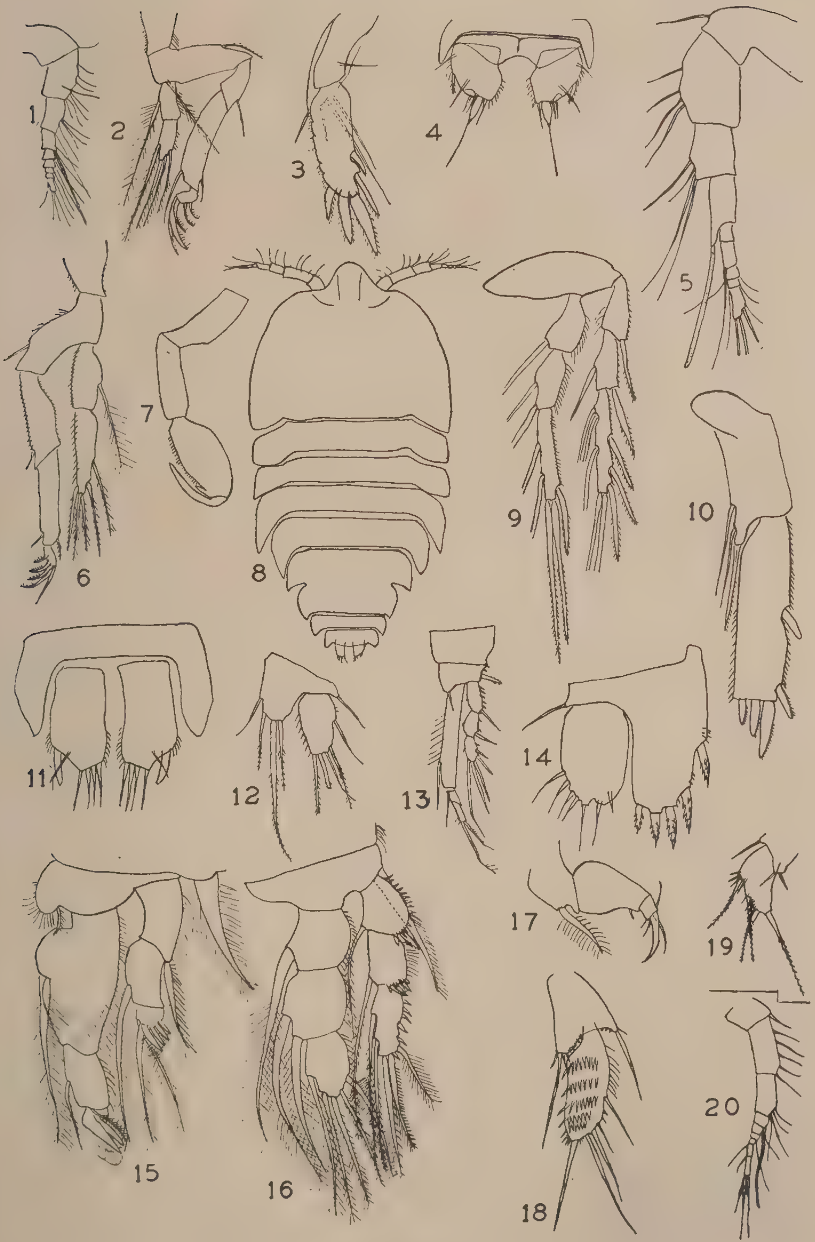
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PLATE 2

Genus *Paralteutha* Scott, 1912

Generic characters. Very similar in general appearance to *Eupelte*, but larger and with the epimeral plates of the fifth metasomal segment better developed. P. 1 with both rami of nearly the same length, first and second segments of the exopod nearly equal. P. 5 with the distal segment nearly rectangular and obliquely truncated at the end.

Paralteutha simile n. sp.

(Pl. II, Figs. 5–11)

Female. General form very similar to that of *Alteutha*, but much larger and less attenuated behind (Pl. II, Fig. 8). Rostrum slightly rounded, not deflexed. Fifth metasomal segment with well developed epimeral plates; distinct epimeral plates also present on urosomal segments. Caudal rami (Pl. II, Fig. 11) longer than wide, 2×1, armed with a very stout spine on the outer corner and four slender setae on the end. A. 1 (Pl. II, Fig. 5) short, 9-segmented, distal part narrowed, less than half the length of the proximal portion; proportionate lengths:

1– 2– 3– 4–5–6–7–8–9
21–18–14–14–5–6–5–3–9

A.2 with Exo. small and slender, biarticulate. Mouth parts as in *P. typica*, Mp. (Pl. II, Fig. 7) elongated, manus with strong claw.

P. 1 (Pl. II, Fig. 6) with rami subequal in length, exopod with first and second segments nearly equal, third very small and provided with four unequal pectinate claws and a smooth seta. P. 2–4 (Pl. II, Fig. 9) differing from those of *P. typica* only in having the last segment of both Exo. and Endo. about as long as the first and second segments combined; spines on the end segments also more distally placed; seta formula:

Leg	Exopod Segment			Endopod Segment		
	1	2	3	1	2	3
P. 2	0	1	2.2.3	1	2	2.2.1
P. 3	0	1	3.2.3	1	2	2.2.1
P. 4	0	1	3.2.3	1	2	2.2.1

P. 5 (Pl. II, Fig. 10) with the distal segment shorter, 3×1, than in *P. typica*, end squarely truncated and armed with three stout spines, the outermost being the larger. Lateral margin with two spines, one near the middle and one at the tip.

Male. Very similar to the female. A. 1 7-segmented, strongly prehensile. P.5 with the segments nearly equal in length.

Length, female, 1.35 mm., male, 1.2 mm.

Color. Eye wine-red body nearly transparent, very pale light yellow.

Occurrence. Two females, one male and one immature female were found in washings from a drifting specimen of the Elk Kelp, *Pelagophycus*, taken from the pier at the Institution.

Remarks. The present species can be distinguished from the type by the slightly greater length of the end segments of the swimming legs, and by the form of P. 5. From *P. villosa* (Brady) it can be distingished by the 9-segmented first antennae and by the proportions of P. 5.

FAMILY TISBIDAE

Genus *Tisbe* Liljeborg, 1853*
Syn.: *Idya* Philippi, 1843
Idyaea Sars, 1909

Generic characters. Body moderately depressed and tapering posteriorly; anterior division sharply distinguished from the posterior. Last segment of the metasome very small, urosome about half the length of the cephalothorax. A. 1 slender, 8-segmented; those of male prehensile. A. 2 with the exopod well developed, 4-segmented. Mandibular palp biramous. Mx. 2 and Mp. uncinate at the tip. P. 1 with both rami 3-segmented, exopod shorter than endopod, last segment obliquely truncated and provided with two slender setae and four unequal penicillate spines. Swimming legs well developed, with the rami nearly equal. Fifth legs slender, proximal segment not very well developed, last segment narrow. Fifth legs of male smaller, but otherwise similar to those of the female.

Tisbe furcata (Baird), 1850
(Pl. III, Figs. 9–12)

Female. The anterior division of the body slightly depressed, elongate oval in outline, and sharply divided from the posterior division. Urosome slender, genital segment distinctly divided. Anal segment very short. Urosomal segments 2-3-4 with ventro-lateral rows of minute spinules, dorsal surface smooth. Caudal rami wider than long, inner and outer apical setae longer than in Sars' figure (Sars, 1903, Pl. LI), almost as long as the genital segment. Genital field (Pl. III, Fig. 9) quite different from that shown in Lang's figure (1936, p. 18), and very similar to that of the two species to be described below. A. 1 moderately slender, second and third segments about equal in length, the terminal part (segments 5–8) more than twice as long as

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* Many modern investigators of the Harpacticoida use the names *Idyaea* of Sars for this genus, since *Idya* Philippi, 1843, is preoccupied. It seems to the writer that according to the rules of nomenclature *Tisbe* Liljeborg, 1853, is not invalidated by *Thisbe* Hübner, 1816, (in Lepidoptera) and must therefore be retained in place of Sars' name *Idyaea*. Vide Norman and Scott, 1906, and Stebbing, 1910.

the fourth segment; proportionate lengths:

$$\frac{1-2-3-4-5-6-7-8}{10-18-17-10-4-5-4-11}$$

P. 1 (Pl. III, Fig. 10) with Exo. about ⅓ longer than Endo. 1. Endo. 2 longer than Endo. 1. P. 2–4 with both rami 3-segmented and nearly equal, seta formula:

Leg	Exopod Segment			Endopod Segment		
	1	2	3	1	2	3
P. 2	1	1	2.2.3	1	2	2.3.0
P. 3	1	1	3.2.3	1	2	3.3.0
P. 4	1	1	3.2.3	1	2	2.3.0

P. 5 (Pl. III, Fig. 11) with the proximal segment small, inner expansion poorly developed, bearing three unequal setae, the middle one extending well beyond the end of the distal segment. Distal segment 3- or 4×1 and armed with five unequal setae, all of them longer than shown in Sars' figure; dorsal surface with six transverse rows of faintly visible spinules.

Male. Much smaller than the female and more slender. A. 1 prehensile and stouter than in female. P. 2–4 as in female. P. 5 (Pl. III, Fig. 12 a) small, distal segment about 2×1, and armed with five setae, the middle one transformed into a strong, minutely setose spine.

Color. Transparent, with transverse bands of bright red on cephalothorax and genital segment, in both sexes. Eye deep red. Egg sac bluish white.

Length, female, 0.93–1.16 mm., male, 0.47–0.80 mm.

Occurrence. Numerous specimens of both sexes were found in material scraped from test plates submerged off the end of the pier during studies by

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EXPLANATION OF PLATE III

Scutellidium lamellipes n. sp.
FIG. 1, ♀, dorsal, ×112
FIG. 2, A. 1♀, ×190
FIG. 3, Endo. 3, P. 1, ×326
FIG. 4, P. 2♀, ×326
FIG. 5, P. 5♀, ×326
FIG. 6, A. 1♂, ×190
FIG. 7, P. 5♂, ×326
FIG. 8, P. 6♂, ×326
Tisbe furcata (Baird)
FIG. 9, Gen. field ♀, ×640
FIG. 10, P. 1♀, ×326
FIG. 11, P. 5♀, ×326
FIG. 12, a, P. 5♂, b, P. 6♂, ×545
Tisbe furcata johnsoni n. var.
FIG. 13, A. 1♀, ×326
FIG. 14, P. 1♀, ×326
FIG. 15, P. 5♀, ×326
FIG. 16, P. 5♂, ×545
Tisbe robusta n. sp.
FIG. 17, P. 5♂, ×545
FIG. 18, P. 5♀, ×326.

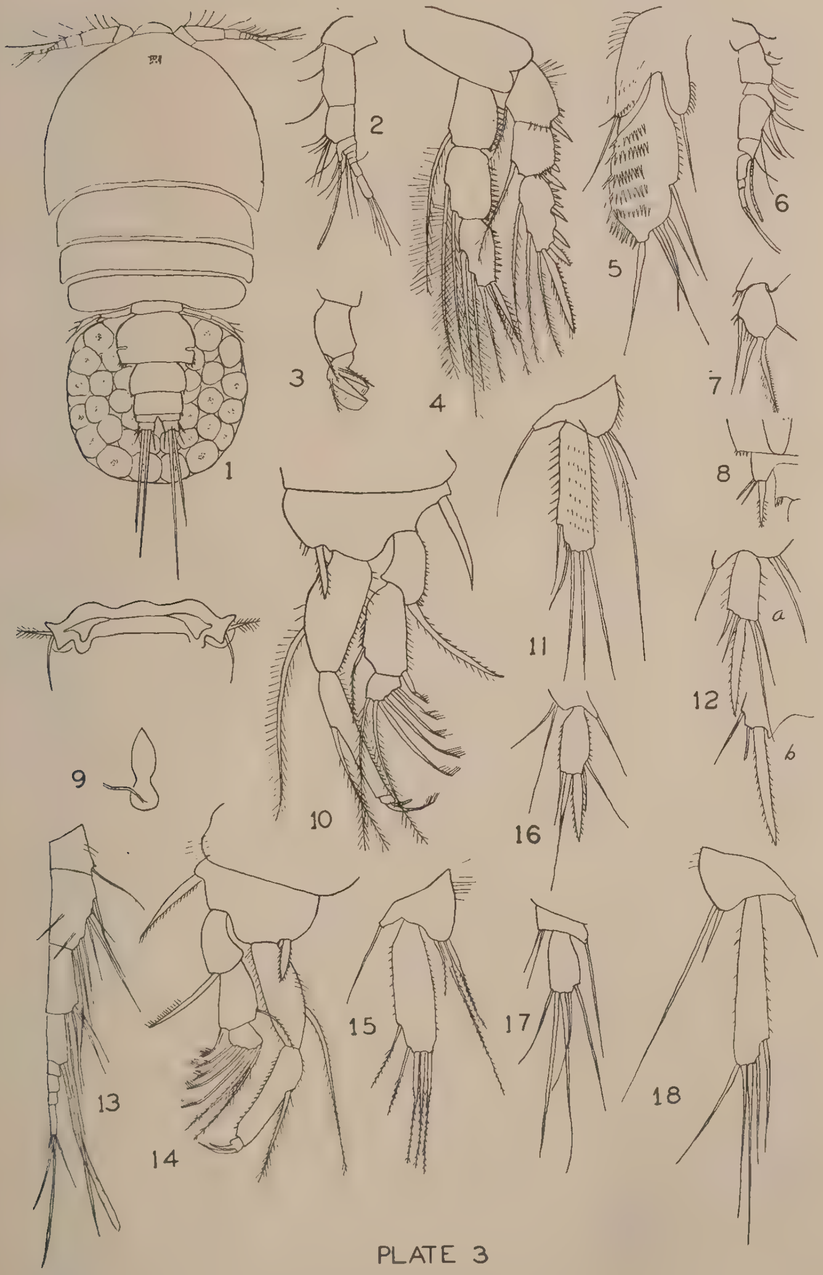
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PLATE 3

Mr. W. F. Whedon upon the fouling of submerged surfaces. Many were also found in material collected from drifting specimens of the Elk Kelp, *Pelagophycus*, taken from the pier, and a few in washings from the brown alga *Eisenia arborea* Aresch from the reef at the Institution. Dr. Walter K. Fisher of the Hopkins Marine Station at Monterey Bay has kindly sent specimens taken from eel-grass in Elkhorn Slough. These agree in all respects with the La Jolla specimens.

Remarks. As noted above, there are several differences between the California specimens and the published descriptions of this cosmopolitan species. The chief differences are in the lengths of some of the setae, and especially in the character of the female genital field. The agreement in the proportions of the body, of the first antennae, and of the first and fifth pairs of legs is very good, however. Professor Lang has kindly examined specimens from the submerged plates mentioned above and agrees in regarding them as *furcata*.

Tisbe furcata (Baird) var. *johnsoni** n. var.

(Pl. III, Figs. 13–16)

Female. Anterior division of the body elongate oval in outline, slightly depressed, and more than twice as long as the urosome. Urosome slender, 4-segmented, genital segment long and disticntly divided. Anal segment very small. Urosomal segments 2–4 with ventro-lateral rows of minute spinules. Caudal rami about as long as wide, next inner apical seta more than twice as long as the urosome; inner and outer apical setae about as long as in the preceding form. A. 1 (Pl. III, Fig. 13) more slender than in that species, second segment longer than the third, terminal part less than twice as long as the fourth segment, last segment shorter than the fourth. Proportionate lengths (average of three measurements):

$$\frac{1-\ 2-\ 3-\ 4-5-6-7-8}{8-20-18-13-5-5-4-8}.$$

Mouth parts very similar to those of the form described above; M. appears to be a little more slender and Mp. a little stouter.

P. 1 (Pl. III, Fig. 14) with Endo. 2 not longer than Endo. 1, and less slender than in the above species, the length being about four times the greatest width. P. 2–4 as in *furcata* P. 5 (Pl. III, Fig. 15) with the proximal segment a little better developed, provided with three unequal inner setae, the longest being much shorter than in *furcata*. The distal segment is definitely less slender, the greatest width being more than $\frac{1}{3}$ the length, the terminal setae are five in number and are also shorter than in the above form. The dorsal surface of this segment likewise bears six transverse rows of minute spinules. The female genital field differs only slightly from that of *furcata*.

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* In honor of Dr. M. W. Johnson of the Scripps Institution of Oceanography, who called attention to these copepods and has studied their habits and life history.

Male. As in the preceding form, except that the outer seta of the distal segment of P. 5 (Pl. III, Fig. 16) is somewhat more proximally placed. The next seta is so feebly chitinized as to be very easily overlooked. The outer apical seta is a strong, minutely setose spine, slightly stouter than in *furcata*.

Color. Nearly transparent, sometimes with faint transverse red markings as in *furcata*.

Length, female, 0.77–0.98 mm., male, 0.50–0.58 mm.

Occurrence. This form occurs endemically in the trays and tanks in the culture rooms at the Scripps Institution where there is a constant supply of flowing sea water pumped directly from the sea. It has not yet been found in any of the numerous other collections made at La Jolla, in spite of a careful search being made for it. All stages of the life history occur in the culture rooms.

Remarks. This variety closely resembles the preceding species. It differs, in the female, in its smaller size and in the proportions of A. 1, of Endo. P. 1, and of the distal segment of P. 5. Professor Lang (personal communication) is of the opinion that this form is only a culture form of *T. furcata*, especially since it has been found only in the culture rooms at the Scripps Institution. That is certainly a possibility, although the conditions under which the animals thrive are not very different from those obtaining in the open sea habitat. It may be that the sea water system offers a more favorable habitat for endemic production than does the natural habitat.

Tisbe robusta n. sp.
(Pl. III, Figs. 17–18)

Female. Form stouter than in the two preceding species. Anterior division of body moderately depressed, expanded in front and gradually narrowing posteriorly. Epimeral plates of metasome separated by deep incisures. Urosome slender, 4-segmented, about half the length of the cephalothorax. Caudal rami slightly broader than long, the two middle apical setae very long, inner and outer apical setae shorter in proportion than in the above variety. Female genital field resembling that of *T. gurneyi* Lang. Egg sac large, subquadrate in outline. A. 1 moderately slender, the second segment slightly shorter than the third, distal part only slightly more than twice as long as the fourth segment; formula:

$$\frac{1-\ 2-\ 3-\ 4-5-6-7-\ 8}{14-28-29-20-7-8-7-19}\ .$$

P. 1 with Exo. about $\frac{1}{3}$ longer than Endo. 1. Endo. 2 about $\frac{1}{5}$ longer than Endo. 1 (37:31), length about three times the greatest width. P. 2–4 about as in the preceding species, Exo. 3, P. 4, being more slender, about 4×1, therein resembling *T. longisetosa* Gurney. P. 5 (Pl. III, Fig. 18) with the proximal segment small, the inner expansion being provided with two very unequal setae, the innermost extending beyond the end of the distal segment. Distal segment slender, 5–6×1, gradually widening distally, and provided with five unequal setae.

Male. Smaller than female, anterior division of body less flattened. Urosome slender, 5-segmented, half the length of the anterior division. P. 1–4 as in female. P. 5 (Pl. III, Fig. 17) smaller, proximal segment very small, inner expansion with two unequal setae. Distal segment nearly rectangular in outline, 2×1, bearing five long, unequal setae, none of them being spinelike.

Color. Not determined.

Length. Female, 1.28–1.38 mm., male, 0.75–0.85 mm.

Occurrence. Numerous specimens of both sexes were found in washings from the Elk Kelp, *Pelagophycus porra*, taken off the pier at the Institution.

Remarks. The chief characters by which this species may be distinguished are the robust appearance of the female, and the character of P. 5 in both sexes.

Genus *Scutellidium* Claus, 1866

Syn.: *Psamathe* Philippi, 1840
: *Machairopus* Brady, 1883

Generic characters. Anterior division of body robust, slightly depressed, cephalic segment about as long as the next three segments combined and evenly rounded in front. Last metasomal segment much smaller than the others, not covered. Urosome abruptly narrower than metasome and about the same length. Genital segment enlarged, partially divided. Anal segment short, incompletely divided. Caudal rami short, nearly as long as wide, terminal setae long, the next to inner being twice as long as the urosome. A. 1 fairly stout, 9-segmented, abruptly narrowing at the fourth segment in most species. A. 2 with the exopod half the length of the endopod. P. 1 with Endo. 1 large and expanded, about as long as the entire Exo., last segment very small, armed with two penicillate spines and one or two small setae. Exo. 3 with penicillate spines and setae. P. 2–4 with both rami 3-segmented and nearly equal. P. 5 with the proximal segment short, more or less bilobed, last segment oblong.

Remarks. The genus *Psamathe* was established by Philippi in 1840 to include a Mediterranean form, *P. langicauda*, and in 1866 Claus erected the genus *Scutellidium* for a Mediterranean species, *S. thisboides*, which is considered to be identical with Philippi's species. In 1924 Wilson called attention to the fact that *Psamathe* is preoccupied, and that the genus must therefore be called *Scutellidium*. In 1936 Lang united *Psamathe* and *Machairopus* Brady, 1883, under *Machairopus*, without stating why he rejected *Scutellidium*. Since the latter name is the older, and not preoccupied, it must be retained. According to Sars the *Scutellidium* of Brady, 1880, is a different form, *Aspidiscus* Norman (=Sacodiscus Wilson).

Scutellidium arthuri Poppe, 1884
(Pl. II, Figs. 15–19)

Female. Very similar to *S. longicauda* (Philippi). Anterior division of body oval in outline, epimeral plates moderately developed, last segment very small, but visible dorsally. Urosome 4-segmented, slightly less than half as long as the anterior division. Caudal rami about as long as wide, bearing two long, unequal setae and several shorter ones. A. 1 about half as long as the cephalic segment, proportionate lengths:

$$\frac{1-\ 2-\ 3-4-5-6-7-8-9}{11-24-10-6-3-2-2-5-9}.$$

Mp. (Pl. II, Fig. 17) with a large curved spine and four setae on the terminal segment.

P. 1 (Pl. II, Fig. 15) with Exo. more slender than in *longicauda*, length of first segment nearly twice the greatest width. P. 2 (Pl. II, Fig. 16) characterized by the presence of a very strong setiferous spine at the outer angle of the second basis, and by the form of Endo. 2, which is as wide as long. P. 3–4 with Endo. more slender; seta formula:

Leg	Exopod Segment			Endopod Segment		
	1	2	3	1	2	3
P. 2	1	1	2.2.3	1	2	2.2.1
P. 3	1	1	3.2.3	1	2	3.2.1
P. 4	1	1	3.2.3	1	2	2.2.1

P. 5 (Pl. II, Fig. 18) with the first segment indistinctly bilobed, distal segment slender, 3×1, with four unequal setae on the lateral border and a slender spine at the tip. Dorsal surface with five transverse rows of spinules.

Male. Similar to female in appearance, but smaller. A. 1 8-segmented, geniculate between the fifth and sixth, seventh very small. Mouth parts and swimming legs as in female. P. 5 (Pl. II, Fig. 19) small, distal segment about 2×1, and provided with four minutely setose setae.

Length. Female, 0.88–0.91 mm., male, 0.74 mm.

Color. Reddish brown on metasomal segments and urosome, lighter on cephalosome.

Occurrence. The predominant species of copepod found in washings from various sea weeds at the Scripps Institution, in company with the species to be described below, and with *Zaus spinatus* Goodsir and several species of *Porcellidium*.

Remarks. The southern California specimens of this species agree with

Poppe's description in all details, except for the smaller size and the color. The species can be identified without dissection by the presence of the large spine on the second basis of P. 2, and by the width of the second segment of the endopod.

Scutellidium arthuri var. *magnum* n. var.

Female. Larger than the above species, and with a deep purple band on the first free segment of the metasome and on the urosome. Remainder of the body very light, nearly transparent. All appendages agree with those of *arthuri*. Male unknown.

Length. Female, 1.4 mm.

Occurrence. Only a few females have been found, in collections containing the typical *arthuri*.

Scutellidium purpurocincta n. sp.
(Pl. II, Fig. 20)

Female. Smaller than *S. arthuri*, but very nearly related to it. A. 1 (Pl. II, Fig. 20) with the third segment distinctly longer than in that species, nearly as long as the second segment, proportionate lengths:

$$\frac{1-\ 2-\ 3-4-5-6-7-8-9}{7-13-11-4-2-2-2-4-6}.$$

First legs as in *arthuri*. P. 2 has the same strong spine on the second basis, but the second segment of the endopod is not as wide as long (25×28). P. 3–4 as in *arthuri*. The distal segment of P. 5 is somewhat more slender ($3\frac{1}{2}\times 1$). Male unknown.

Length. Female, 0.65–0.68 mm.

Color. Body very light brown, with purple on the three free segments of the metasome and on the bases of the rami of the swimming legs.

Occurrence. A few females, some ovigerous, have been found in collections with the preceding species.

Remarks. This species is clearly distinguished from all the other known species of the genus, except *S. arthuri*, by the large spine on the second basis of P. 2; it is distinguished from *arthuri* by its color and distinctly smaller size, and by the greater length of the third segment of the first antenna. The female genital field is also quite different from that of *arthuri*.

The value of the proportionate lengths of the antennal segments in separating species is not clearly established. In the closely related genus *Tisbe* the proportions of the leg segments are used in separating the species (Gurney, 1927, p. 498–500, and Lang, 1934, p. 16–18). Also, the length of the antennal segments is used by Gurney (1927, p. 515) in the diagnosis of the genus *Amphiascopsis*.

*Scutellidium lamellipes** n. sp.
(Pl. III, Figs. 1–8)

Female. Very similar to *arthuri* in form of body, but larger and lighter in color. A. 1 (Pl. III, Fig. 2) with the third segment slightly longer than in that species, proportionate lengths:

$$\frac{1-2-3-4-5-6-7-8-9}{14-25-16-5-3-3-3-7-11}.$$

Mouth parts as in *S. longicauda.*

P. 1 stouter than in either *longicauda* or *arthuri*. Exo. 1 being about $1\frac{1}{2}\times 1$. Inner seta of Endo. 2 (Pl. III, Fig. 3) much reduced in size, and attached at the outer distal corner of the segment. P. 2 (Pl. III, Fig. 4) differs from that of *arthuri* in having no spine on the second basis, and in having Endo. 2 longer than wide ($1\frac{1}{2}\times 1$). P. 3–4 as in *arthuri*. P. 5 (Pl. III, Fig. 5) with the proximal segment distinctly bilobed, and nearly as large as the distal segment. Distal segment broad, $2\frac{1}{4}\times 1$, and provided with a single terminal seta, four unequal setae on the posterior border, and a series of eight to ten small, slender spinules on the anterior border near the terminal seta. Dorsal surface provided with five transverse rows of spinules.

Male. Very similar to the male of *arthuri*. A. 1 (Pl. III, Fig. 6) 8-segmented and strongly prehensile, geniculate between fifth and sixth segments seventh very small. P. 5 (Pl. III, Fig. 7) small, less elongated than in *arthuri*, length slightly more than greatest width. P. 6 (Pl. III, Fig. 8) represented by a small protuberance at the posterolateral corner of the genital segment, bearing a small spine and two setae.

Length. Female, 0.99–1.1 mm., male, 0.74 mm.

Color. Very light cream.

Occurrence. With *S. arthuri* and *Zaus spinatus*, one of the most numerous copepods found on various sea weeds on the reef at the Scripps Institution.

Remarks. This species is very similar to *S. longicauda* (Phil.), but may be distinguished by its larger size and by the structure of the fifth legs.As noted above, it may be distinguished from *S. arthuri* by its lighter color and by the character of P. 2 and P. 5.

FAMILY DIOSACCIDAE

Genus *Diosaccus* Boeck, 1872

Diosaccus spinatus Campbell, 1929
(Pl. II, Fig. 14)

Female. Anterior division of body distinctly compressed, cephalosome large and deep, one-third longer than thorax. Rostrum prominent, depressed.

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* Referring to the broad fifth feet.

Mouth parts similar to those of *D. tenuicornis* (Claus). P. 1 also very similar to that species, the exopod being slightly more slender. P. 5 (Pl. II, Fig. 14) very characteristic, inner expansion of proximal segment broad, and extending to the end of the distal segment, provided with five stout, coasrsely denticulated setae. Distal segment broad, $1\frac{1}{2} \times 1$, and provided with six slender setae. Caudal rami closely approximated, greatest width about two-thirds the length. Males not yet found in any of the La Jolla collections.

Length. Female, 0.99 mm.

Color. Deep red on the first free thoracic segment, on the genital segment, and on the upper segments of the swimming legs, remainder of the body golden yellow.

Occurrence. Only a few females have been found in southern California, in material collected from *Phyllospadix* at Point Loma, San Diego, and in scrapings from submerged test plates at the Scripps Institution's pier. They agree in all details with Campbell's original description, except for their smaller size.

FAMILY AMEIRIIDAE

Genus *Ameira* Boeck, 1864

Ameira longipes Boeck, 1864

(Pl. II, Figs. 12–13)

Female. Body slender, anterior division slightly compressed. Posterior division cylindrical, slightly tapering and nearly as long as the anteriol division. Last segment of urosome about as long as the preceding. Cauda, rami quadrangular, wider than long. A. 1 nearly as long as the cephalosome. second segment the longest and broader than the first. P. 1 (Pl. II, Fig. 13) with Exo. slender, 3-segmented and slightly more than half as long as Endo. Endo. 1 nearly three times as long as Endo. 2 and 3 together; third segment narrow and nearly twice as long as the second. P. 5 (Pl. II, Fig. 12) with inner expansion of proximal segment broad, extending to the middle of the distal segment, provided with four unequal setae, the next outermost being much the longest. Distal segment well developed, widest near the base and narrowing gradually toward the end, provided with five setae, the outermost being placed at the middle of the lateral margin. Males not yet found in La Jolla collections.

Length. Female, 0.77 mm.

Color. Very pale, nearly transparent.

Occurrence. A few females were found in material collected from the submerged test plates previously mentioned. They agree in all details with Sars' description of this species.

SUMMARY

1. The copepod fauna of the marine littoral zone of southern California

is very rich in individuals and species. It includes a number of cosmopolitan forms as well as many whose exact range is unknown.

2. The present paper describes sixteen species belonging to five families of Harpacticoida, including eight species and two varieties new to science. Further studies of the group are in progress.

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CLASSIFICATION AND TAXONOMY

by

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Every active person has some degree or kind of interest in classification.

Even a young school boy makes daily, often hourly, use of simple forms of classification though they be nothing more than expression of his views of qualities or attributes. Thus, he groups his playmates as good, fair, or poor at certain kinds of play, his teachers as harsh or kind, his lesson assignments as easy or hard. The teacher in turn, uses many classifications which are little, if any, more intricate. Likewise the parents, the duties of the day are light or heavy, the food is as good as usual or better or worse, the neighbors are various. That is to say, classification is not something foreign to our daily experience. It is not always dull and dreary.

But what of taxonomy, that form of classification by which one seeks to express the natural relationships, the kinships, of animate things accurately in a specialized terminology? Off hand, it may be supposed that only specialists have any real interest in such expression, especially when obscured under the more or less intricate maze of technicalities ordinarily involved. However, experience shows that a surprisingly large number of people who are lacking in technical information do appreciate the efforts of experts to classify according to biological relationships and that they like to know the reasons for applying certain technical names to the groups with which they have acquaintance. It is also true that persons who lack familiarity with any taxonomic group, persons who are familiar with very few, and even persons who are familiar with many while lacking expert knowledge of some, often show interest in taxonomic terminology strange to them if they have good reason to believe that it indicates or suggests natural relationships accurately.

Still, it is entirely possible for discussions of taxonomy to be intolerably dull. A good illustration occurred in my own experience. As a graduate student in 1900 I was asked to give a report before a Zoology Seminar on the paper "Structure and Classification of the Arthropoda" by Sir E. Ray Lankester. Before I had finished most of the students and most of the professors were asleep. The highly frequent impact upon their ears of group names being marshalled into appropriate ranks was too much for auditors denied the time necessary for current analysis. Furthermore, not one of those present at that particular seminar was working with the Arthropoda and much of the terminology was unfamiliar if not actually strange to most of them. That is to say, they lacked facilities essential for instant understanding and clear appreciation of the rapidly succeeding points of discussion, conditions necessary for sustaining their interest and keeping them alert.

Considerations such as the foregoing may serve to illustrate the fact that both classification and taxonomy influence wide varieties of persons for wide varieties of reasons and that the prime characteristics of these systems of grouping are influenced to greater or less extent by every individual who employs them. For example, even the most rigid of zoological taxonomists may be rather indifferent to botanical usage in a casual reference to certain plants which he chooses to mention. To the extent that his usage modifies or conflicts with botanical taxonomy he exerts an influence upon the stability and general authority of botanical nomenclature. That such conditions are resented, deplored and condemned by authentic, authoritative specialists in both classification and taxonomy is well known but there seems to be little that they can do about it, no more in fact than can be done by the outraged language purist when confronted by new examples of distorted word forms or absurd meanings of words in colloquial speech. So long as the general population, inexpert or even ignorant, can find practical use for either methods or words, many individuals are sure to insist upon practices which are confusing as well as annoying to the trained and habituated expert.

Strangely enough, not all of the confusion in taxonomy can be charged against the ignorant or presumptuous intruders upon its sacred precincts. The differences in opinion between authorities themselves are numerous and wide. One expert throws species together or reduces many to the status of races or varieties. Another, equally eminent, splits existing species up into new species requiring new names which include his own as authority. Sometimes there is definite and positive disagreement concerning the application of a species name (other group name either, for that matter). Sometimes there is refusal to accept existent grouping as being truly indicative of degrees of kinship, and there is constant changing of names and ideas of relationships as new or better information is acquired.

As a matter of fact, much of the confusion and many of the inaccuracies of taxonomy are inevitable results of the history of development of biological sciences and of inherent weaknesses of human nature and intelligence. Nor is Nature herself entirely blameless in the matter, refusing as she does to play according to taxonomic rules and insisting as she does on introducing all kinds of vagaries, sometimes in most exasperating ways at most inauspicious moments. The fact that taxonomy survives and improves in spite of numerous strongly injurious influences affords excellent proof that it is needed. Not only is it needed by authoritative taxonomists themselves but it is needed by any person, however unskilled or uninformed, who has occasion to consider biological group relationships or to establish group or individual identities.

This widespread need for taxonomy (or some kind of dependable system of biological classification) deserves more consideration, especially sympathetic consideration, than it usually receives. If a golf player hits a ball two hundred yards into a questionable position, he is permitted to play a "provisional" ball so that loss of time and energy may be avoided until the status of the first ball has been determined. In almost all human activities similar provision must be made for flexibility in order to avoid costly delays or exhausting repetitions or to permit progress. Nevertheless, there are authoritative taxonomists in all fields who insist that an identification, or a suggestion of relationship, must not be made by an inexperienced observer or without exhaustive examination of the material. They deplore the accumulation and use of data based on provisional or incomplete identification by others at the same time that they refuse to give a provisional opinion of their own for temporary use.

I believe that there are thousands of teachers of biological sciences in the United States, and thousands of amateur observers, who could and would use taxonomy to the pleasure and profit of themselves, their students, and their friends if properly encouraged instead of being kept in constant fear of censure or reprimand. After all, the authorities, themselves, lacked experience once. Indeed, they are not entirely free from error in spite of their rigidity. Even an amateur can keep records accurately and the unauthoritative use of a technical name need do no serious harm if it be designated carefully and clearly as temporary or provisional. As a matter of fact, population studies of significant extent can not be carried on at all, even by authorities, if precise identification is demanded for each individual specimen. This is particularly true of mixed populations but it is almost equally true of a *natural* population of a single species. To a greater or less extent identities must be *assumed* because of resemblance to the sample specimen or specimens examined critically, i.e. identification is mostly provisional and must be reviewed if some condition arises which throws suspicion on parts of the population. However, the provisional identification found to be wrong may be an asset instead of a liability if the records are reliable enough to trace the specimens which have been misnamed, or appear to have been misnamed.

Species splitting, the sometimes arbitrary creation of two or more new species out of one old one, has been mentioned as a source of confusion in taxonomy. As bad, if not worse, is the practice of giving a name to a specimen without making sure that it really lacks a valid name. Those guilty of the first practice are almost invariably authorities, or at least experienced workers. Those guilty of the second practice are most generally amateurs or novices who can perform a real service to science by refraining from giving or in any way changing the technical names of any and all living creatures.

Other sources of confusion in taxonomy and in its correct application may be mentioned as follows:

(a) Too many species have been named and described from specimens belonging to an extreme, i.e. the "type specimen" may be much larger or much smaller than is common in the species or may show other extremes.

(b) Descriptions or drawings or both may be insufficient, may be inaccurate, may be vague, or may emphasize wrong characters.

(c) Many species are highly unstable, or variable. Even in relatively stable species such a character as the length-breadth ratio may be seen completely reversed in certain specimens. One can only guess what the differences may be in less observable characters.

(d) Intergrading (apparent or real) species cause no end of trouble. Sometimes specimens can be found side by side which may belong to either one of two distinct species so far as "recognition" characters are concerned. Not only so but the steps in transition to resemblance can be traced from common forms of the two species associated in the particular locality.

(e) Lack of clear recognition characters is another exasperating cause of trouble in identification. The type specimen may have beautiful recognition marks (e.g. spines or protuberances of particular form) which may be distorted or completely lacking in most of certain populations. Other species are just as troublesome because they have no reliable mark of any kind which surely distinguishes them.

(f) Numerous characteristics of most organisms change with age. If the "type specimen" was very old it may be quite difficult to find a large population resembling it satisfactorily. Young specimens may be wholly unrecognizable. It is safe to say that even today many thousands of invertebrate animals are known only by one stage of their existence to any authority.

(g) Life cycles are known completely for relatively few organisms. For many of those imperfectly known identification has been attempted only for one phase. In a population study this deficiency leaves ample room for trouble in identification although it may be far better to recognize one phase than none.

Notwithstanding its weaknesses, deficiencies, and endless liabilities to trouble taxonomy is a highly superior form of classification. For one thing, it is based on the single fundamental idea of kinship of all living things, thus insuring a degree of stability and continuity not possible for the ordinary kinds of classification in which the whims of the moment or of the individual may and do play so large a part. Nevertheless, taxonomy is not so nearly perfect as some of its devotees appear to think. Furthermore, as a human device, it appeals strongly to human desires to use. On our farms, in our gardens, in our door yards, in our lily ponds, under our door-steps, even in our balanced aquaria exist populations well worth study as populations, as waxing and waning aggregations, as interdependent associations, all demanding more or less accurate use of taxonomy in aid of fruitful observation and understanding. Opportunities to apply taxonomy in common service exist everywhere, and expansion of its usefulness should be encouraged.

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OCEAN PASTURAGE IN CALIFORNIA WATERS[1]

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FOR ages, seafaring men have had their interest stirred, at certain times and places by conspicuous conditions of the sea due to the presence of microscopic plants (phytoplankton). Most often, their attention has been attracted by very distinct discolorations (''red water,'' ''brown water,'' ''yellow water,'' etc.), although the odor of sea water has been strongly prominent also sometimes (''stinking water''). In addition, there have been times and places when fishermen have had trouble in handling their nets or gear because of coatings of slimy material consisting of microscopic plants. Such experiences alone are sufficient to raise questions concerning the causes and relationships of the observed conditions.

In more recent years, because of increasing attention to details of ocean characteristics, less conspicuous occurrences and displays of phytoplankton phenomena have led to comprehensive studies of the microscopic plants and their activities. From such studies it has come to be understood that phytoplankton distribution in seasons (or other periods), in depths, in localities and in latitudes has direct relationships to movements of air and water masses (regular and irregular, systemic and turbulent), and that it both influences and is influenced by turbidity, density, temperature, light, dissolved substances, co-existent organisms and indefinite numbers of other chemical, physical and biological characteristics of sea water. In particular it is generally recognized to-day that phytoplankton constitutes the basic food supply (ocean pasturage) which directly or indirectly furnishes sustenance for commercial fishes and other animals at the same time that it draws much of its own sustenance from them. Not only so, but phytoplankton furnishes much of the food used by sedentary animals useful for human food (oysters, etc.) or harmful to human enterprise (''fouling organisms'' so injurious to ship bottoms and other structures exposed to attack).

As recently as 1919 practically nothing was known concerning phytoplankton in the Pacific Ocean. Indeed, an authoritative paper published in Philadelphia as late as 1927 commented on the small numbers of kinds of diatoms and their thinness of population in the Pacific, although local investigations were already showing the contrary fact for this most important contributing group. Because of the necessity of knowing names and identities when discussing or investigating the relationships of any natural object or group of objects to conditions in the sea much time had to be given to mere identification and naming of specimens in the first few years of researches at the Scripps Institution of Oceanography at La Jolla, California. Thereby it was found that although more than two hundred species of phytoplankton organisms live in the East Pacific, less than fifty species ever become so abundant as to attract special attention, even from specialists. Although diatoms are distinctly most important in most years in most localities, the group of dinoflagellates sometimes takes a temporary lead in production of ocean pasturage.

Fortunately, while learning identities, it was possible to accumulate other kinds of data concerning the components of phytoplankton. The records showed that no single species was ever able to hold the lead in production over a long period of time, rarely longer than ten days. Also it appeared that production tended to be best before July, although there might be a difference of a week or two in this tendency at two stations only a little more than one hundred miles apart. Twenty years of investigations have revealed that no two years were alike at either of two stations and that two years of unusually warm water (1926 and 1931) were poorly productive of both diatoms and dinoflagellates at both stations.

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About three thousand catches by boat at offshore stations have shown that phytoplankton may reach notable abundance more than one hundred miles from shore and at depths as great as seventy meters, large numbers, however, rarely being taken below fifty meters. Sometimes many diatoms appear at lower levels though few at the surface, sometimes many appear at the surface when numbers are small below, and sometimes rather large numbers may be found at all seven of the levels sampled at a particular station. Unexpectedly, large numbers in good condition are taken sometimes from levels below large numbers in poor condition. As a matter of fact, no large numbers of specimens in dead or decadent condition have been observed below any dense population in vigorous condition, although one might suppose that many would die and sink.

A notable difference of abundance of phytoplankton between two stations indicates a difference between them in respect to chemical composition of the water, physical constitution of water masses, behavior of water masses, climate or meteorological conditions, or animal populations. If such a difference in phytoplankton populations does no more than prevent hasty or rigid conclusions and inferences from being asserted on the basis of close similarity of too few chemical or physical observations, it is worth something. When it confirms the validity of an observation of an unexpected difference in those conditions it becomes distinctly helpful. That is to say, microscopic plants naturally detect and respond to chemical and physical conditions of their environment which are too delicate for one to detect by routine methods in a laboratory. Therefore, proper attention to their responses to unnoted changes in those conditions may lead to correct interpretations or to changes in routine which lead to better if not to full understanding.

In some localities most of the oxygen in sea water is derived from the air. In other localities (or at certain periods) most of it is derived from phytoplankton. In the one case no immediate effect on the chemical composition of sea water is necessarily involved in the processes of introduction.

In the other case. incident and immediate changes occur in substances containing carbon, sometimes involving indefinite series of chemical changes in surrounding sea water. So far, no one has ever evaluated the contribution of oxygen by phytoplankton in the ocean although chemists, physicists and biologists are agreed that in the matter of oxygen transfer alone the microscopic plants hold a prominent place in the network of environmental influences. Although the twenty years of phytoplankton research have shown conclusively that periodicity of production and occurrence is not predictable for any restricted or specific place or depth level, they have shown that cloudlike aggregations of diatoms and dinoflagellates run a course of increase and development during which much might be learned about the influences of phytoplankton through oxygen production (and consumption). While the requirements of trustworthy investigations of this problem under natural conditions may be too expensive at present, it is none the less true that the opportunity exists.

Similar statements may be made concerning investigations of occurrence and distribution of carbon, phosphorus, nitrogen and their compounds as well as other elements and substances not mentioned so frequently. Although many people seem to feel confident that relationships of influences of temperature may be easily detected, described, and evaluated, it is more probable that a clear understanding of any but the grossest manifestations of temperature conditions is very difficult to obtain. Still, there is no doubt of the fact that adequate phytoplankton data may aid substantially in understanding coincidental phenomena of temperature. Probabilities seem to be even better for such influences as viscosity, density and light.

Repeated cruises continue to show that phytoplankton abundance has a recognizable relationship to turbulence, upwelling, oceanic drift and to major and minor currents. It is entirely reasonable to expect that understanding of these relationships will improve rapidly as more data of the same kind as those yielding these results are accumulated.

So far, inshore and offshore conditions are not clearly understood as to manner and degree of influence but much is apparent already in fact. For example, certain species which reach abundance offshore are rarely noticeable inshore (and *vice versa*). Also, certain localities near shore appear to be more productive at certain periods or seasons while certain localities offshore appear to be more productive at other periods or seasons. Here there can be no question that familiarity with phytoplankton populations in their native habitats will help to clarify these relationships either when time and effort can be spared for them directly or as data accumulate otherwise. Possibly even better progress can be made toward understanding of characteristics of deeps and shallows by giving careful attention to phytoplankton relationships in or about them.

Practically nothing is known concerning the more direct effects of run-off from land, not to mention the indirect effects. Even Gran appears to have rejected an earlier opinion that run-off enriched sea water, but it is surely reasonable to suppose that this enrichment ensues, nevertheless. Whatever the facts may be, it seems certain that the phytoplankton must be depended upon for evidence leading to a final solution. Doubtless this solution will be delayed a long time because of cost of specific researches required by it, but the phytoplankton data accumulated by the Scripps Institution affords a sound foundation upon which to base the necessary investigations, not only of the nutrient influences of run-off but also of dilution and sedimentation influences.

To geologists (especially petroleum geologists) plankton diatoms are highly interesting because of their relationship to problems of oil-producing sediments. If one can learn why diatom frustules are deposited here and not there, and why sometimes no diatom deposits can be found at or near localities which are known to yield them abundantly, he may be able to account for some of the vagaries of deposition. Some of the observed conditions of occurrence suggest the probability that many diatom frustules dissolve during long support or transport without sinking to the bottom, thus maintaining in the water a fair supply of siliceous material to be used by their own kin.

So far Scripps Institution work on phytoplankton has contributed nothing to direct knowledge concerning the continuous series of changes of organic wastes in the sea. We know that the little plants must use other things besides carbon dioxide, but we do not know what forms of the various substances are most valuable in their activities, nor how they meet fluctuations in amounts of preferred materials. However, the records of occurrence of phytoplankton bring necessary information to the point where intelligent selection of species and localities may be made for conducting observations.

Concerning relationships with other organisms much that has been said above will apply. However, it seems probable that phytoplankton data are even more important for any one who undertakes to identify and trace food chains (*e.g.* diatoms, copepod, sardine, mackerel, squid; or diatom copepod, hydroid) involving either free-living or sedentary animals. Still, the food relationship is not the only one. For example, researches indicate that phytoplankton may become so abundant sometimes as to seriously injure many surrounding animals, possibly by mere crowding, possibly by clogging of the gills, possibly by direct poisoning in some cases.

Contribution No. 123

INTERNAL WAVES IN THE GULF OF CALIFORNIA*

By

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Between February 13 and March 19, 1939 the "E. W. Scripps," research vessel of the Scripps Institution of Oceanography occupied fifty-three oceanographic stations in the Gulf of California. On the basis of observations of temperature and salinity which were taken at every station at a series of depths a chart of the dynamic topography of the surface relative to the 1500-decibar surface was derived, but this chart does not indicate any regular exchange of water between the Gulf and the adjacent part of the Pacific. It shows a sequence of separate highs and lows which are associated with alternating downward and upward displacements of the isopycnic surfaces and suggests the existence of internal waves with amplitudes as one-tenth the depth of the Gulf.

Let ρ be the density, depending upon the temperature and salinity of the water. The vertical displacements, as represented by σ_t curves ($\sigma_t = 10^3(\rho - 1)$ are clearly seen in a longtitudinal section (Figure 7) based on data from stations along the center line of the Gulf, as shown on the small map to the left in the figures. It should be observed that the vertical scale is greatly exaggerated relative to the horizontal, the ratio between vertical and horizontal scales being equal to 1/800. The profiles of a series of isobaric surfaces relative to the 1500-decibar surface are shown to the right in the figure.

These observations have been discussed by H. U. Sverdrup (1940; in press) who concludes that the wavy character of the isobaric surfaces might be due to the presence of a standing internal wave, the period of which would lie between 6.3 days and 7.65 days, probably closer to the former value. This explanation is consistent with boundary conditions. The wave would be of first (fundamental)

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order with respect to the vertical axis, the vertical displacement vanishing at surface and bottom only, and three nodes inside the Gulf make it of fourth order with respect to the horizontal axis. A node at the mouth of the Gulf indicates that one has to deal with a free oscillation. The wave length of 1000 kilometers near the mouth of the Gulf indicates that the two progressive waves which combine to the standing wave there have velocities of propagation of 175 cm/sec which decrease towards the closed end of the Gulf. For further description of these waves and internal waves generally reference should be made also to Defant (1929), Sverdrup, Johnson and Fleming (in press), and W. H. Munk (in press).

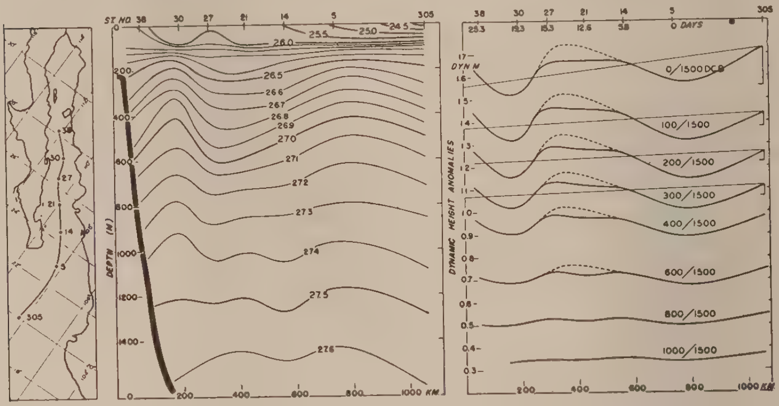

Figure 7. Vertical distribution of density (σ_t) and profiles of isobaric surfaces referred to the 1500-decibar surface along a section in the Gulf of California, as shown on the map at the left in the figure. (After H. U. Sverdrup.)

Internal waves are accompanied by large horizontal velocity components at the bottom. It will be shown later (Figure 9) that the horizontal velocity at the bottom of the Gulf attains a maximum value of 20 cm/sec which is sufficiently large to exert a pronounced influence upon the processes of sedimentation. Within a standing wave the horizontal velocity component reaches a maximum near the location of nodes and one may expect that only large-sized particles settle in their vicinity. On the other hand, anti-nodes are characterized by very small horizontal currents which would permit small particles to be deposited at the bottom.

Such an influence of internal waves upon the distribution of sediments was pointed out by R. R. Revelle (1939) who found the average median diameters of bottom samples in the Gulf to vary in a regular manner along a north-south direction, corresponding to an internal wave with three nodes. This evidence is not conclusive, but it suggests that the particular wave-form of fourth order with respect to the horizontal axis does not constitute an isolated phenomenon but appears to be of common occurrence. The evidence would be greatly strengthened if it could be shown by means of theoretical considerations that the observed oscillation represents one of the possible natural oscillations in the Gulf.

Such a wave might be caused by an outside periodic disturbance the period of which would have to be closely related to one of the free periods of oscillation in the Gulf. The lunar-fortnightly tide has a period of 13.6 days and a theoretical amplitude which is one sixth the amplitude of the principle semi-diurnal lunar tide. If the length of one of the natural periods of the Gulf would correspond closely to 13.6 days an oscillation with this period would be dominant, but if a natural period close to 13.6 days does not exist, the lunar-fortnightly tide may cause an oscillation of approximately half this length, 6.8 days, corresponding to the observed period of oscillation of the Gulf.

Hence, it will be necessary to investigate theoretically the question whether the picture which has been derived from observations is in agreement with theoretical considerations and whether lunar forces may be responsible for the formation and maintenance of an internal wave of the observed type.

A body, defined by its distribution of mass and its dimensions, has a definite set of natural frequencies. These frequencies can be easily calculated in the case of uniform bodies of simple geometrical shape but the corresponding calculation becomes very complicated when applied to the waters of the Gulf of California within which the distribution of density is a function of depth (Figure 9) and the boundaries of which are determined by the topographic features of the Gulf (Figure 8). J. E. Fjeldstad (1933) has developed the theory of progressive internal waves in a channel of constant depth, provided that the density distribution does not change in a horizontal direction. W. H. Munk (in press) has treated the cases of progressive or standing waves, assuming constant depth and appreciable horizontal density gradient and of standing waves, assuming variable depth but negligible horizontal density gradient. For rigorous derivations reference is made to these papers, and here it will be attempted only to outline the latter theory, to explain its application, and to discuss the results pertaining to the Gulf.

Previous investigations of wave phenomena (Defant, 1929) have shown that in a long narrow channel the earth's rotation will tend to produce oscillations in a plane perpendicular to the length of the channel, but its effect upon the chief wave motion along the channel will be small and can in first approximation be neglected. For that reason the problem reduces to a two-dimensional analysis.

We shall assume the x-axis along the direction of propagation of the wave, the z-axis perpendicular to the surface, where $z = 0$ represents the undisturbed surface, $z = H$ the bottom. (Figure 8.) Let u and w represent the components of the velocity of the water along the x and z axes respectively, ρ the density, p, the pressure, and η the vertical displacement. Let $\rho_0(z)$ denote the density in equilibrium condition and define ρ_1 by

$$\rho = \rho_0(z) + \rho_1(x, z, t)$$

Let

$$p_1 = g \int_0^z \rho_1(x, z, t)$$

Neglecting second-order terms, the fundamental equations of hydrodynamics take the form

$$\frac{\partial u}{\partial t} + \frac{1}{\rho_0}\frac{\partial p_1}{\partial x} = 0 \tag{1a}$$

$$\frac{\partial w}{\partial t} + g\frac{\rho_1}{\rho_0} + \frac{1}{\rho_0}\frac{\partial p_1}{\partial z} = 0 \tag{1b}$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{1c}$$

$$\frac{\partial \rho_1}{\partial t} + w\frac{\partial \rho_0}{\partial z} = 0 \tag{1d}$$

To investigate a progressive or standing wave with period $T = \dfrac{2\pi}{\sigma}$, we assume:

$$\left.\begin{array}{ll} \textit{Progressive wave} & \textit{Standing wave} \\ u\,(xzt) = U\,(xz)\sin\,(kx - \sigma t) & ,\ u\,(xzt) = U\,(xz)\cos\,(\sigma t) \\ w\,(xzt) = W\,(xz)\cos\,(kx - \sigma t) & ,\ w\,(xzt) = W\,(xz)\cos\,(\sigma t) \\ p_1(xzt) = P_1\,(xz)\sin\,(-\,kx + \sigma t), & p_1\,(xzt) = P_1\,(xz)\sin\,(\sigma t) \\ \rho_1\,(xzt) = R_1\,(xz)\sin\,(-\,kx + \sigma t), & \rho_1\,(xzt) = R_1\,(xz)\sin\,(\sigma t) \end{array}\right\} \tag{2}$$

Substitution of either set of assumptions into equation (1) eliminates the function of time, and the remaining four equations in four unknowns can be solved for $W(x\,z)$:

$$\frac{\partial^2 W(xz)}{\partial z^2} - g\frac{\varphi(z)}{\sigma^2}\frac{\partial^2 W(xz)}{\partial x^2} = 0 \tag{3}$$

where

$$\varphi = -\frac{1}{\rho_0}\frac{\partial \rho_0}{\partial z} \tag{3b}$$

The substitution $W(x\,z) = W(z)\sin(k\,x)$ reduces the partial differential equation (3) to the total differential equation:

$$\frac{d^2 W(z)}{dz^2} + \left(\frac{1}{c}\right)^2 g\,\varphi\,W(z) = 0 \tag{4}$$

where the wave length $\lambda = \frac{2\pi}{k}$ and the velocity of propagation, $c = \frac{\lambda}{T}$.

This is the differential equation derived by Fjeldstad for the case of constant depth. It can be shown, however (Munk, in press), that this substitution $W(x\,z) = f(z)\cdot F(x)$ is inconsistent with the general problem and consistent only for a basin of constant depth, wherefore, assumptions (2) leading to equation (3) must be used when treating the case of variable depth.

Assumptions (2) referring both to standing and progressive waves, satisfy the basic laws of hydrodynamics and lead to differential equation (3). This is true because the standing wave may be considered a superposition of two progressive waves of equal amplitude but opposite direction, and both progressive waves are proper solutions, hence their sum, the standing wave, must also be a solution. On the other hand, the two wave-forms behave in a very different manner with regard to boundary conditions and it can be shown (Munk, in press) that the solution referring to progressive waves cannot be applied to a basin of variable depth. This indicates that a standing wave can exist in a basin in which neither of the two progressive waves can exist, which may be considered as making up the standing wave.

In order to obtain values for the periods of natural frequency, σ must be computed from the differential equation (3), subject to boundary conditions:

$$W = 0 \text{ at } x = 0 \tag{5}$$

since a node is located at the mouth of the Gulf (Figure 7), and

$$W = 0 \text{ at } z = 0 \tag{6}$$

since the vertical motion caused by an internal wave at the surface is always small enough to be neglected. Finally, the kinematic boundary condition at the bottom, namely, that all flow must take place *along* the boundary, is expressed by

$$W = mU \text{ along the bottom, where } m \text{ denotes the slope.} \tag{7}$$

Let W be expanded in a Fourier series:

$$W(xz) = \sum_{i=1}^{n} W_i(z) \sin (k_i x) \dot{C}_i(o) \tag{8}$$

where $k_i = i\pi/2L$, L, the length of the basin, and $C_i(o)$ a constant so chosen that $\dot{W}_i(o) = 1 \left(\dot{W}_i(z) = \frac{dW_i}{dz}\right)$

With these substitutions we obtain for equation (3)

$$\frac{d^2 W_i(z)}{dz^2} + \frac{g\,\varphi(z) k_i^2}{\sigma^2} W_i(z) = 0 \quad (i = 1, 2, \ldots n) \tag{9}$$

Boundary condition (5) is already satisfied. Boundary condition (6) gives

$$W_i(o) = 0 \tag{10}$$

Boundary condition (7), with the aid of the equation of continuity, yields

$$\sum_{i=1}^{n} \left[W_i(z) \sin (k_i x) + \dot{W}_i(z) \frac{m(x) \cos (k_i x)}{k_i} \right] \dot{C}_i(o) = 0 \tag{11}$$

In the Fourier summation (8), n must be at least equal to two in order to satisfy all boundary conditions of a basin of variable depth and must be larger than two to give a good approximation. By making n sufficiently large we can approximate as closely as we wish any velocity distribution corresponding to an observed wave.

We note that equation (9) represents n equations of the same type as equation (4), which Fjeldstad has developed for the case of constant depth. Each of these equations describes on internal wave of wave length $\lambda_i = \frac{4L}{i}$ and can be integrated numerically according to the method used by Fjeldstad (1933). In this manner we obtain values for $W_i(z)$ and $\dot{W}_i(z)$ at all depths. The internal wave can then be considered as the result of n internal waves of equal period but different wave lengths, superimposed upon one another.

In order to apply boundary condition (11) we shall divide the length L of the basin into r equidistant intervals with values of x ranging from $x_1 = 0$ to $x_r = L$ (Figure 8). By means of an accurate topographic section of the basin one can find for all values of x_j $(j = 1, 2, 3 \ldots r)$ the corresponding slope m_j and depth z_j. Let us then *assume* a definite value for the parameter σ and obtain $W_i(z)$ and $\dot{W}_i(z)$. for all values of z_j by means of numerical integrations. If we define

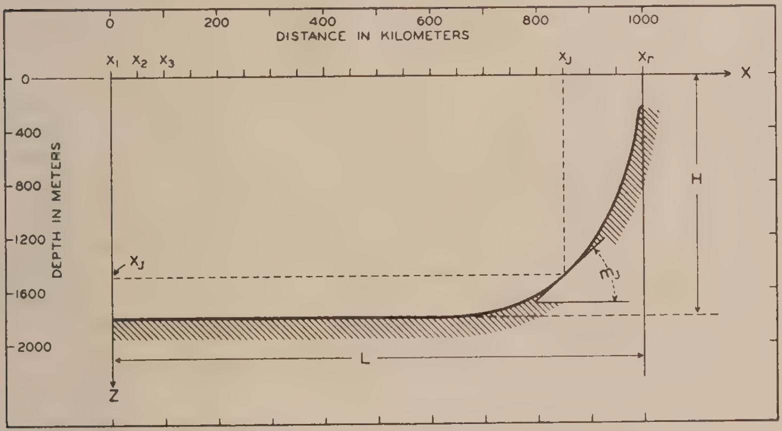

Figure 8. Schematic topography of the Gulf of California and notation used in numerical integration.

$$K_{ji} = W_i(z_j)\sin(k_i x_j) + \dot{W}_i(z_j)\,\frac{m(x_j)\cos(k_i x_j)}{k_i} \tag{12}$$

boundary condition (11) becomes simply

$$\sum_{j=1}^{r}\sum_{i=1}^{n} K_{ji}\dot{C}_i(o) = 0 \tag{13}$$

Munk (in press) has devised a method to test how well boundary condition (13) is satisfied. It calls for the evaluation of a determinant D which will vanish for every value of σ which corresponds to a natural frequency. This, however, is true only for an infinite value of n, for otherwise a Fourier series will give an approximation only to the actual velocity distribution, and D will not vanish completely but will reach a minimum.

For $n = 3$,

$$D = \begin{vmatrix} \sum_{j=1}^{r} K_{j1}K_{j1} & \sum_{j=1}^{r} K_{j1}K_{j2} & \sum_{j=1}^{r} K_{j1}K_{j3} \\ \sum_{j=1}^{r} K_{j1}K_{j2} & \sum_{j=1}^{r} K_{j2}K_{j2} & \sum_{j=1}^{r} K_{j2}K_{j3} \\ \sum_{j=1}^{r} K_{j1}K_{j3} & \sum_{j=1}^{r} K_{j2}K_{j3} & \sum_{j=1}^{r} K_{j3}K_{j3} \end{vmatrix} \qquad (14)$$

D can now be calculated for various values of σ and the natural frequencies can be determined because the value of D must be at a minimum when σ corresponds to a natural frequency.

The bottom topography of the Gulf of California is quite complicated but observations at the deepest stations indicate that to a considerable distance from the mouth continuous communication between the various depressions is present above 2000 meters. It seemed therefore justifiable to choose an "effective" depth which remains close to 1800 meters throughout the larger portion of the Gulf, but decreases regularly in the inner part.

At about 29° latitude the channel becomes very shallow and two islands, San Esteban and San Lorenzo, rise above the surface. Waves will be reflected before they reach this point or lose their energy by friction and interference. Hence we may consider this the inner end of the Gulf, and may neglect the portion north of the islands, although the Gulf deepens and widens again, and extends 350 kilometers further inland.

It is generally known that the "effective" length of a bay with regard to a wave phenomenon is not identical with its actual length, but depends upon its width at the open end. A correction formula has been derived which, in this case, gives an "effective" length of 1000 kilometers, roughly 20 per cent longer than the actual length.

Fjeldstad's theory for basins of constant depth was applied to the outer portion of the Gulf of California. Figure 9 illustrates the results obtained by this theory. They compare favorably with those obtained from observations.

	c	H
Theory	167 cm/sec	675 m
Observations	175 cm/sec	500–600 m

where c represents the velocity of propagation, H the depth of maximum amplitude of oscillation.

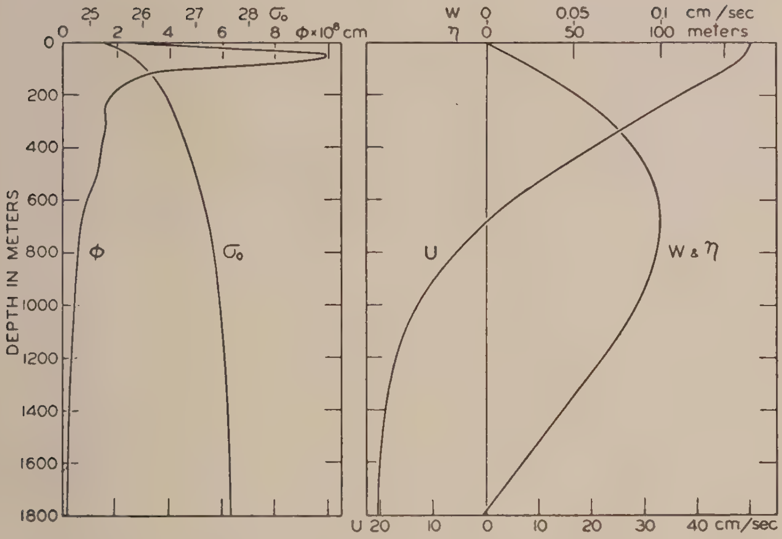

Figure 9. *Left:* Average vertical distribution of density and density gradient along the center line of the Gulf of California.

Right: Horizontal and vertical velocity components and vertical displacement as functions of depth in the outer portion of the Gulf of California.

The calculation of D was carried out for three values of i only. For investigating an approximately weekly period values of $i = 4$, 5, and 7, corresponding to wave-lengths near the mouth of 1000 km, 800 km, and 570 km were chosen, whereas in the case of the fortnightly period values of $i = 3$, 4, and 5 were chosen corresponding to wave-lengths of 1333 km, 1000 km, and 800 km. These particular components were most satisfactory because they gave a low value for D, as illustrated in the following tables:

$T = 6.4$ *days*	*Values of i*	*5-6-7*	*3-4-5*	*4-5-6*	*4-5-7*
	$D \times 10^{-27}$	130	123	63	25
$T = 14$ *days*	*Values of i*	*2-3-4*	*2-3-5*	*2-4-5*	*3-4-5*
	$D \times 10^{-37}$	26	54	6.4	4.0

A further examination (Munk, in press) shows that in both cases a wave dominates which near the mouth has a wave length of 1000 km, decreasing toward the closed end. The nodal regions of both waves must approximately coincide and the distribution of sediments may be consistent with the presence of either wave.

In a vertical direction the weekly wave is primarily of the first order, whereas the fortnightly wave is of the second order. The observed distribution of density indicates that a first-order wave dominates but the presence of a second-order wave is not excluded and may account for the fact that the observations appear to give a smaller value of H, the depth of maximum vertical oscillation.

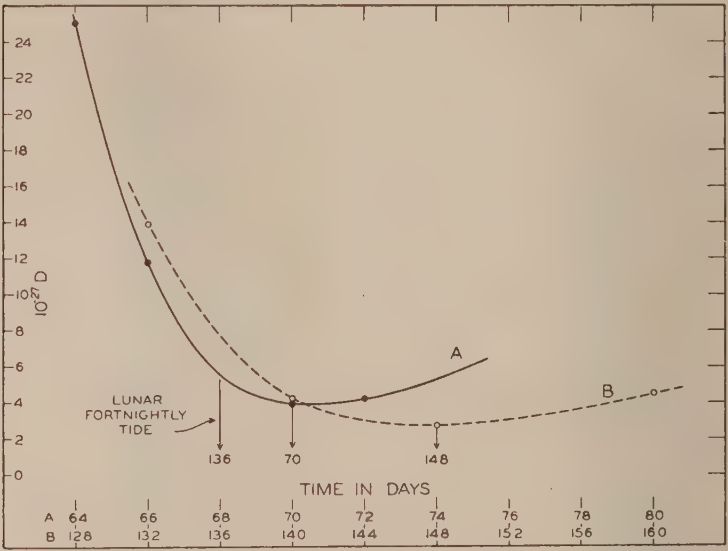

Figure 10. Results obtained by numerical integration indicating two periods in the Gulf of California of natural frequencies of 7 days and 14.6 days, respectively, and their relations to the lunar fortnightly tidal period.

The main results of the numerical integrations are presented in Figure 10 according to which minima correspond to periods of 7 days and 14.8 days. The fact that one minimum falls at a period of 7 days is in good agreement with the conclusions based on observations, particularly because the computed oscillation is, as already explained, of a character similar to the observed one. Twice this period of seven days comes closer to the lunar-fortnightly period of 13.6 days than the minimum obtained near 14.8 days, indicating that resonance is more likely to occur in the case of the seven-day period than in the case of the 14.8 days, and that the seven-day period, therefore, may dominate. Thus, the theoretical examination fully confirms Sverdrup's interpretation of the observations from the Gulf of California.

The writer wishes to acknowledge the help of Dr. H. U. Sverdrup, who suggested this investigation and without whose advice and encouragement it could not have been completed. The writer is also indebted to Dr. H. Bateman for his help in finding a solution to the general differential equation, and to Dr. L. Lek and Mr. F. Brunner for having carried out many of the tedious calculations.

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Contribution No. 124

STUDIES ON MARINE BACTERIA. I. THE CULTURAL REQUIREMENTS OF HETEROTROPHIC AEROBES[1]

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The observations of Issatchenko (1914), Benecke (1933), Waksman (1934), ZoBell (1938) and others have established that bacteria are quite widely distributed in the sea where they probably play an important role influencing chemical, physico-chemical, geological and biological processes. However, due primarily to the widely divergent analytical procedures which have been used by various investigators studying the distribution and activities of marine bacteria, the quantitative results obtained by different workers in different parts of the world are not comparable.

The nutrient medium used to grow the bacteria has been one of the greatest variables. A large variety of nutrient ingredients in varying concentrations and combinations which yield markedly different results have been used and recommended for plate count media. Following literally Standard Methods (1933) of water analysis some workers have used fresh water to prepare their media either with or without the addition of salt, while others have used synthetic or natural sea water although, as will be pointed out below, most marine microorganisms have fairly specific salt requirements. Still other workers have regarded the bacteria of the sea as not unlike those in the soil and have treated them accordingly with discordant results. As pointed out by Lipman (1929), within relatively narrow limits the composition of the medium is an important determinant of the number and kinds of organisms found in the sea. At the present time there are almost as many kinds of nutrient media in use for estimating the marine bacterial population by plate count procedure as there are workers in the field and, as will be shown below, they yield very different results.

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The following report is concerned primarily with a systematic study of the cultural requirements of marine bacteria with special reference to the preparation of a nutrient medium for heterotrophic aerobes which will yield maximum and reproducible counts. While it is recognized that no one combination of nutrients or cultural conditions can provide for the growth of all kinds of bacteria which occur in the sea, the unquestioned value and extensive use of plating procedures for estimating the bacterial population of marine materials, for studying cultural characteristics and for obtaining pure cultures for physiological studies makes it highly desirable to have data which will permit the adoption of media which will yield maximum and reproducible counts. Moreover, such information on the nutritional requirements of marine bacteria will prove to be invaluable in studying their physiological activities and in estimating their importance as biochemical agents in the sea.

Observations during the last eight years on the occurrence and distribution of bacteria in the sea have afforded an excellent opportunity to study their cultural requirements. In analyzing sea water, bottom sediment or other marine materials it has required little additional effort to use two or more combinations of media rather than merely one and moreover, this procedure has served to check the results. Thus, over a period of years, it has been possible to compare the relative growth-promoting properties of several different media which have been proposed for the growth of marine bacteria. New formulae have been developed as indicated by the cumulative results and tried.

EXPERIMENTAL METHODS

Sea water for analysis was collected by means of a bacteriological sampler described by ZoBell and Feltham (1934) which insures exclusion of any extraneous contaminating material. Radially central portions of the cores of bottom deposits obtained with a Trask coring tube (Hough, 1939) were dissected out for analysis, using aseptic precautions in all manipulations. Except where otherwise designated, the samples were collected at places which are remote from possibilities of terrigenous contamination. Autoclaved sea water or a mixture of 75 per cent sea water with 25 per cent distilled water was used to dilute the samples, the samples being diluted sufficiently to provide for the growth of 30 to 300 colonies on the plates which were acceptable.

In the preliminary work a medium similar to that recommended by Standard Methods (1933) of water analysis was used:

Bacto-peptone	5.0 gm
Beef extract	2.0 gm
Bacto-agar	15.0 gm
Sea water	1000.0 ml

This will be referred to as Formula 1 and has been used as the standard for comparing many other media. The sea water used in the preparation of the media, unless otherwise stated, was collected and aged for several weeks in 5 gallon glass bottles to insure uniformity in the composition.* The reaction of Formula 1 is pH 7.6 without adjustment after sterilizing at 120° C. for 20 minutes. Special care was taken to cool the nutrient agar to 42° C. before pouring into the inoculated plates because, as has been pointed out by ZoBell and Conn (1940), most marine bacteria are thermo-sensitive, many of them being injured by even short exposure to temperatures exceding 42° C. The inoculated plates were incubated at 22° C., it having been shown that prolonged exposure at higher temperatures is lethal to some marine bacteria. The colonies which developed on the plates after five to ten days were counted, using a 3.5X engraver's lens and a Stewart counting chamber.

SALINITY REQUIREMENTS

Fresh water, either with or without the addition of salts, has been quite commonly used for estimating the bacterial population of marine materials. Lloyd (1930), Burke (1934) and others report that marine bacteria grow equally well in either fresh water or sea water media. Conversely, Berkeley (1919), Korinek (1926) and Lipman (1926) maintain that the mere dilution of sea water materially reduces the number of marine bacteria which will grow. According to Korinek (1927) marine bacteria can be distinguished from non-marine forms upon a basis of their specific salt tolerance.

*Matudaira (1939) and others have noted a marked difference in the growth-promoting properties of sea water collected at different depths, stations and dates on the growth of diatoms which is attributed to something organic in nature. Similarly we have noted that bacteria behave differently in media prepared with sea water collected from different stations. These differences in the growth-promoting properties of sea water disappear within a few weeks when the sea water is stored or "aged" at room temperature presumably because the organic fractions which are responsible for the differences are oxidized by the increased bacterial activity which accompanies the storage of sea water in glass bottles (ZoBell and Anderson, 1936a).

The validity of these antithetical views was tested by preparing nutrient media which were similar in all respects except salt content. For this purpose, Formula 1 was used with the sea water diluted with distilled water to give various concentrations. These media were inoculated with appropriately diluted samples of raw sea water and their relative growth-promoting properties determined. Table I gives the protocol of a representative experiment. To facilitate the comparison of results the "growth index" for each medium is recorded. The growth index is the expression of the average plate counts as ratios on a basis of the plate counts on the standard medium being 100.

TABLE I

Relative Numbers of Bacteria in a Sample of Raw Sea Water which Formed Colonies in Nutrient Media Prepared with Different Concentrations of Sea Water

Per cent sea water	100	75	50	25	10	5	0
Per cent distilled water	0	25	50	75	90	95	100
Bacteria in sample 9A	218	196	139	87	38	24	13
Bacteria in sample 9B	231	204	143	82	35	28	21
Average number of bacteria	224	200	141	84	36	26	17
Growth index	**100**	89	63	41	16	12	8

Over thirty samples of sea water and nearly as many samples of marine bottom deposits collected from various stations off the coast of Southern California have been analyzed in this way. Without exception appreciably more bacteria grew in the media prepared with sea water than in corresponding fresh water media. Only 55 to 65 per cent as many colonies appeared on plates of media prepared with sea water diluted one half with fresh water, and in fresh water media only 5 to 20 per cent as many bacteria developed as in that prepared with undiluted sea water. Similar results were obtained regardless of whether tap water, distilled water or glass re-distilled water was used, thus ruling out the possibility of the fresh water carrying any toxic agent. From the data it is quite apparent that sea water and not distilled water or tap water should be used in the preparation of nutrient media for marine bacteria.

In the experimental procedure outlined above 1.0 ml. of raw sea water or mud diluted with sea water was used to inoculate approximately 10 ml. of nutrient agar. It follows, then, that upon the inoculation of the fresh water medium in which no sea water was used in its preparation, there is around 10 per cent of sea water in the medium, and the other media will actually contain a somewhat larger percentage of sea water than that designated in the table. Sea water can be almost completely excluded from the fresh water media by the use of fresh water for diluting mud and other marine materials containing a rich microflora, but another complication is introduced: the viability of marine bacteria is rapidly weakened by such treatment. In a few experiments in which fresh water dilution water was used there were only 3 to 5 per cent as many bacteria developed in the fresh water medium as in that prepared with sea water.

Bacteria in bottom deposits are slightly less sensitive to salinity changes than are those which occur in water as shown by the composite data in Table II. Those obtained from terrestrially polluted bays (Mission Bay and San Diego Bay) seem to grow almost equally well in fresh water or sea water nutrient media, or at least there are about as many bacteria capable of growing in fresh water as in sea water media. The growth of terrigenous or fresh water bacteria is inhibited by sea water. Several samples of sewage, tap water, soil and microflora from the buccal cavity of man were plated with media containing different concentrations of sea water and the results are summarized in Table II. The samples of microflora from the buccal cavity were obtained by having several laboratory workers rinse their mouths with sterile saline and pooling the washings.

TABLE II

Relative Numbers of Bacteria from Marine and Terrestrial Sources which Developed in Nutrient Media Prepared with Different Concentrations of Sea Water

	Samples	*Per cent of sea water in medium*					
Source of Inocula	*Analyzed*	100	75	50	25	10	0
		Average growth index					
Raw sea water	31	**100**	93	65	38	17	9
Marine mud	18	**100**	89	61	46	28	19
Mission Bay mud	4	**100**	107	117	142	156	106
San Diego Bay mud	3	**100**	108	131	142	139	114
Mission Bay water	5	**100**	103	115	108	118	97
Sewage	13	13	27	51	79	106	**100**
Tap water	8	4	10	28	58	105	**100**
Soil (near sea)	7	48	56	79	90	97	**100**
Soil (inland)	6	15	23	40	66	89	**100**
Mouth microflora	5	9	15	41	78	93	**100**

It is noteworthy that soil bacteria collected from inland valleys were much more sensitive to sea water than those in soil samples collected on the Scripps Institution grounds adjacent to the sea. However, this is not surprising because ZoBell and Mathews (1936) have shown that from 70 to 95 per cent of the bacterial flora being transported by off-sea breezes are of marine origin and that marine bacteria occur in the atmosphere 30 miles inland. Most of the bacteria which are transported inland from their marine environment to which they are indigenous soon perish; more resistant ones may survive for a time and a few probably have become acclimatized to the soil with attendant changes in their properties (Burke and Baird, 1931; Burke, 1934). Consequently, one would expect to find more marine-like bacteria in the soil near the sea than farther inland. According to ZoBell and Mathews (1936) the microflora transported by off-sea breezes is predominately terrestrial in character, fewer than half of the bacteria being able to grow in sea water media. Thus, the wind plays an important role in the interchange of bacteria between the land and sea and helps to account for the fact that 5 to 20 per cent of the bacteria in the sea are capable of growing in fresh water media and a like proportion of the bacteria in fresh water or terrestrial materials are capable of growing in sea water media. However, as will be elaborated elsewhere, certain bacteria are euryhaline.

Although a large proportion of the bacteria in marine materials are definitely stenohaline upon initial isolation, they rapidly lose their saline specificity following laboratory cultivation. After a few weeks most cultures which initially would grow only in sea water media grow equally well in either sea water or fresh water media (ZoBell and Michener, 1938).

The specific salt requirements of bacteria from oceanic environments as compared with those from brackish water, polluted bays, fresh water or terrestrial sources may account for many of the contradictory opinions expressed in the literature concerning the characteristics of marine bacteria. It is astonishing to note how many kinds of water bacteriologists have designated "sea water" without any qualifying statements concerning the salinity, isolation from oceanic circulation or other properties. Since much of the early work was done on samples obtained from seas or surface water having a low salinity, bays, harbors, estuaries and other coastal waters which are subject to varying degrees of dilution with freshwater and terrigenous contamination, one does not know if the workers were dealing with either marine bacteria or sea water.

An attempt has been made to ascertain just what there is in sea water which makes it indispensable for the initial growth of most marine bacteria, but the complete explanation has not yet been found. As shown by the data in Table III, the addition of 3.0 per cent

TABLE III

Relative Number of Bacteria in 8 Samples of Raw Sea Water and 6 of Marine Mud which Developed in Comparable Media Prepared with Various Salt Solutions

	Natural sea water	*3.0% sodium chloride solution*	*Artificial sea water*	*Isotonic sea salt solution*	*Distilled water*
			Average growth index		
Raw sea water	**100**	56	77	89	7
Marine mud	**100**	61	74	94	16

sodium chloride to fresh water nutrient medium to render it isotonic with sea water materially improves results, but such a medium is not as good as sea water for the growth of marine bacteria. Synthetic or artificial sea water prepared with several salts including a trace of ferric phosphate in the hypothetical combinations in which they occur in sea water (Lyman and Fleming, 1940) is better than the sodium chloride solution, but it fails to provide for the growth of as many bacteria as natural sea water. There seems to be something in sea water besides its mineral constituents which is essential for the growth of marine bacteria because not even isotonic concentrations of sea salt were as good as natural sea water (Table III). The sea salt was prepared by evaporating sea water in vacuo and then adding distilled water to prepare nutrient media. Allen (1913) found that certain diatoms would not grow in synthetic media unless a little sea water was added, an observation often made on other organisms.

Contrary to popular conception, marine bacteria do not tolerate high concentrations of salts much better than they tolerate hypotonicity. This is illustrated by the results summarized in Table IV,

TABLE IV

Relative Numbers of Bacteria in 12 Samples of Raw Sea Water which Developed in Nutrient Media Prepared with Sea Water to which Different Salts Were Added

			Per cent of salt added			
Salts added to sea water	0	1.5	3.0	6.0	12.0	18.0
			Average growth index			
Sodium chloride	**100**	96	88	41	12	3
Artificial sea water	**100**	90	72			
Sea salt	**100**	81	49			

which were obtained by inoculating media prepared with sea water to which different concentrations of sodium chloride, artificial sea water constituents or evaporated sea salt were added. Surprisingly enough, sea water rendered hypertonic with evaporated sea salt or artificial sea water constituents was more toxic than that rendered hypertonic by the addition of sodium chloride. This is probably because marine bacteria are more sensitive to large concentrations of certain specific salts found in sea water than they are to hypertonicity. The substitution of potassium chloride and sodium sulphate for sodium chloride revealed that sulphate and potassium are tolerated in concentrations two to three times higher than that in which they occur in sea water. Similar procedures showed that calcium and magnesium occur in sea water in concentrations which are near the limits of tolerance, double this amount inhibiting the growth of many marine bacteria. According to Korinek (1926, 1932) fresh water bacteria are much more resistant to changes in osmotic pressure than are marine bacteria. This was also recognized by Coupin (1915), Lipman (1926), Berkeley (1919) and others.

Further studies on the effect of diluted and concentrated sea water upon bacterial multiplication established that while marine bacteria are sensitive to salinity changes, they grow equally well in nutrient sea water throughout a salinity of 30 to 40‰. The growth of about ten per cent of them is inhibited if sea water is diluted until the salinity is 25‰ or if it is concentrated to a salinity of 45‰. Since the salinity of sea water the world over is well within these limits, comparable results should be obtained as far as salinity is concerned, regardless of where sea water is collected for the preparation of bacteriological media.

EFFECT OF NITRATE

Probably due primarily to the work of Gran (1902) and Drew (1911, 1914) on the abundance in the sea of denitrifying or nitrate-reducing bacteria whose demonstration requires the use of nitrate in the medium, many subsequent workers have continued to add nitrate in varying amounts to nutrient media used for the cultivation of marine bacteria. Though differing otherwise in composition, the media used by Berkeley (1919), Lipman (1926), Bavendamm (1931), Gee (1932) and many other leading marine microbiologists all have nitrate in common. The more or less general adoption of nitrate as a standard constituent of nutrient media recommended its use in our preliminary surveys on marine bacteria (ZoBell and Feltham, 1934) but controlled experiments with media without nitrate failed to confirm its merits.

The addition of 0.005 to 0.10 per cent of potassium nitrate to Formula 1 did not increase the plate counts and there was some evidence of the higher concentrations being inimical. This is illustrated by the results which are summarized in Table V. Similarly, the nitrate neither increased the size of the colonies nor the number of kinds of bacteria which developed. Sodium nitrate was not unlike potassium nitrate in its effect upon the growth and multiplication of marine bacteria. In the course of the investigations nitrate was added to several other combinations of nutrients which were tried but in no case did it prove to be beneficial.

TABLE V

Effect of Different Concentrations of Potassium Nitrate on the Plate Counts of Marine Bacteria. The Growth Indices Rather than the Absolute Plate Counts Are Given

Sample	*Number of Samples*	*Concentration of Potassium Nitrate* 0	0.005	0.01	0.05	0.10
		Average Growth Index				
Sea water	6	**100**	102	95	102	87
Sediment	5	**100**	99	101	96	84

According to Gran (1902), certain marine bacteria can use nitrate as the sole source of nitrogen. It is now recognized that many bacteria are endowed with this ability, but the author is aware of no bacterium for which nitrate is indispensable for its nitrogen nutrition. Nitrate-reducing, denitrifying or nitrate-assimilating bacteria have been found to grow just as well in the absence of nitrate as in its presence. This generalization applies to nearly a hundred pure cultures which have been tested and it substantiates the plate count observations that the addition of nitrate to nutrient media does not enhance the growth of marine bacteria. Moreover, just as many nitrate-reducing or denitrifying organisms are found on plates of nutrient media without nitrate as on plates of similar media containing 0.05 per cent potassium nitrate. Therefore, it would seem that there is no reason for adding nitrate to the medium unless the latter is to be used for a specific purpose for which nitrate is required; for example, testing bacteria for their ability to reduce nitrates.

PHOSPHATE

Lea and Nichols (1936) believe that a lack of sufficient phosphate in natural waters not infrequently limits the growth of bacteria, but the work of Waksman and Carey (1935) and Renn (1937) indicates that it is doubtful if phosphate limits the growth of bacteria in the sea. Nevertheless, it may be desirable to supplement the phosphate content of sea water used in the preparation of nutrient media where, besides supplying the phosphorus requirements of bacteria, it might also function as a buffer and in other ways. Certain workers (Reuszer, 1933; Lipman, 1929; Bedford, 1933) recommend the addition of 0.005 to 0.10 per cent of potassium phosphate to nutrient sea water media while others make no provision for supplementing the phosphorus content. The effect of this variance in technique on the growth of marine bacteria has been investigated.

Dibasic potassium phosphate in concentrations ranging from 0.005 to 0.1 per cent were added to Formula 1. The reaction of each medium was adjusted to pH 7.6 after autoclave sterilization. The media were inoculated with 1.0 ml of appropriately diluted samples of raw sea water or marine mud. Table VI shows the relative numbers of colonies which developed on each medium. Included in Table VI are also the results obtained with and without the use of dibasic potassium phosphate in Reuszer's (1933) and PPP media:

Peptone	1.0 gm	Proteose peptone	2.0 gm
Glucose	1.0 gm	Bacto peptone	3.0 gm
K_2HPO_4	0.05 gm	Beef extract	2.0 gm
Agar	15.0 gm	Agar	15.0 gm
Sea Water	1000.0 ml	Sea Water	1000.0 ml

The three nutrient media were not used simultaneously so the data in Table VI should not be misconstrued as comparing their relative merits. The data show how the addition of phosphate influenced the growth of bacteria in each medium. It will be observed that within the limits of experimental error bacterial development was indifferent to the presence of the added phosphate.

TABLE VI

EFFECT OF DIBASIC POTASSIUM PHOSPHATE ON THE GROWTH OF MARINE BACTERIA

Nutrient Medium	*Samples Tested*	*Concentration of K_2HPO_4*				
		0	0.005	0.010	0.025	0.10
		Average growth index				
Formula 1	6	100	104	98	103	91
Reuszer's	6	100	105	102	101	84
PPP	8	100	97	104	98	96

There is some evidence of the lower concentrations (0.005 to 0.01 per cent) of dibasic potassium phosphate improving the media slightly but the results are not conclusive. Definitely, it is not inimical to the growth of marine bacteria unless used in nutrient sea water media in concentrations exceeding 0.025 per cent. Since marine bacteria are quite sensitive to changes in the hydrogen-ion concentration, the use of phosphate might be indicated in media containing little or no peptone or other good buffers.

The apparent inhibitory effect of 0.1 per cent potassium phosphate is probably not due to any direct effect of the salt on the bacteria because, as shown by Mallman and Gallo (1931) the growth and metabolism of many bacteria is improved by the use of this much sodium or potassium phosphate in nutrient media. When added to sea water the phosphate tends to precipitate the calcium, iron and other salts from solution, and in large concentrations tends to materially affect the mineral composition of sea water. This complication can be largely obviated without diminishing the theoretical or real benefit of additional phosphate by the use of one which is relatively insoluble, such as tricalcium or ferric phosphate. Since iron salts have proved to be highly beneficial, the use of ferric phosphate is recommended.

IRON AND OTHER MINERALS

While testing the tolerance of marine bacteria for iron salts, it was observed that the addition of small quantities of either ferrous or ferric salts to nutrient sea water media materially increased the plate counts. Although sea water itself probably contains enough iron (Thompson and Robinson, 1932; Cooper, 1935) to support an extensive bacterial population and the peptone, beef extract and other media constituents also contain more iron than that required for the cell substance of the bacteria which grow in such media, the iron might not be in the right form or concentration to provide for optimal conditions. Evidence will be presented elsewhere which suggests that iron like aluminum compounds precipitate from solution or otherwise inactive toxic agents such as silver or copper, for example, which occur in sea water and which may have an unfavorable oligodynamic action on microorganisms. It is also probable, as suggested by Baudisch (1932), that iron in the proper form and concentration acts as a biocatalyst and otherwise stimulates bacterial growth. Allen (1913), Gran (1931) and others have observed that the addition of iron to sea water cultures stimulates the growth of diatoms. The compilation of culture media by Levine and Schoenlein (1930) shows that iron salts are widely used to promote the growth of fastidious microorganisms.

Preliminary experiments revealed that from a viewpoint of their availability and effect on bacterial development, ferric chloride, ferrous sulphate, ferric citrate and ferric phosphate were the best iron salts to use in nutrient sea water media. Table VII summarizes the results obtained when using different concentrations of these salts in a medium prepared with 0.3 per cent Bacto-peptone, 0.2 per cent proteose peptone, 0.2 per cent beef extract and 1.5 per cent agar in sea water. The reaction of each medium was adjusted to pH 7.6 with the addition of N/1 NaOH. The media were inoculated in duplicate with six different samples of sea water and the colonies were counted after 7 days incubation at 22° C. The results are reported as ratios upon a basis of the plate count on the control medium to which no iron was added being 100.

TABLE VII

RELATIVE NUMBER OF BACTERIAL COLONIES WHICH DEVELOPED ON NUTRIENT SEA WATER AGAR WITH DIFFERENT CONCENTRATIONS OF IRON. THE AVERAGE PLATE COUNTS OF SIX SAMPLES OF SEA WATER ARE GIVEN EXPRESSED AS RATIOS UPON A BASIS OF THE PLATE COUNT ON THE CONTROL MEDIUM SANS ADDITIONAL IRON BEING 100

	Molecular	*Concentration in per cent*			
Salt used	*Weight*	0	0.001	0.01	0.10
		Growth Index			
Ferric citrate	356.58	100	143	163	107
$FeCl_3 \cdot 6\ H_2O$	270.31		132	154	82
$FeSO_4 \cdot 7\ H_2O$	278.02		134	141	90
$FePO_4 \cdot 4\ H_2O$	222.93		149	178	126

It will be observed that the enrichment of the medium with 0.001 to 0.01 per cent of the iron salts increased the plate counts 32 to 78 per cent. One-tenth per cent of ferric citrate or ferric phosphate was less stimulating and this concentration of ferric chloride or ferrous sulphate was slightly toxic. Not only are the plate counts significantly higher in media enriched with favorable concentrations of iron salts; the colonies are larger and more kinds of bacteria develop on iron-enriched media than on control media to which no iron is added.

Further experiments with various nutrient combinations and different iron salts show that ferric salts are no better than ferrous salts for stimulating the growth of marine bacteria in nutrient sea water media. It has been noted that regardless of whether ferrous or ferric iron is added to the medium, both forms are present following its sterilization and inoculation, the concentration of each depending upon the oxidation-reduction potential of the medium, its pH and the initial concentration of iron added. Being highly ionized and acidic, high concentrations of sulphates or chlorides of iron are more toxic than similar amounts of the poorly soluble and nearly neutral phosphates or citrates of iron. Moreover, since the addition of even low concentrations of iron chlorides or sulphates precipitate certain constituents from sea water necessitating the filtration of the media and making it difficult to adjust the pH recommends the use of citrates or phosphates of iron which do not present these difficulties. Statistically different nutrient combinations have yielded somewhat larger plate counts when ferric citrate or ferric phosphate has been used than when ferrous sulphate or ferric chloride has been used in the optimum concentration. It is much easier to prepare clear media of the proper pH when the iron is added as the citrate or phosphate rather than as the chloride or sulphate.

Although there are many species of marine bacteria which can utilize citrate as a sole source of carbon and energy, the addition of citrate to peptone medium does not increase the number of colonies which develop from sea water or sediment samples. Therefore, the beneficial effects from the addition of ferric citrate are to be ascribed to the iron and not the citrate. However, as pointed out above, additional phosphate in nutrient media might serve a useful function which would indicate the use of ferric phosphate as a source of iron in preference to ferric citrate. Further experiments with the use of these two iron salts alone and together in different concentrations in different combinations of nutrients show that nothing is gained by using both ferric citrate and ferric phosphate. There was little difference observed in plate counts, colony size or diversity of species, regardless of whether ferric citrate or ferric phosphate was added to the media, but under most conditions the use of either one increased appreciably the plate count on nutrient sea water agar.

Since both ferric citrate and ferric phosphate are only slightly soluble in sea water, an excess of either is not toxic. Almost equally good results were obtained from the use of any concentration of either salt between 0.001 and 0.025 per cent. For convenience and simplicity, 0.01 per cent, 0.1 gram per liter, has been selected for routine use. In no combination of nutrient sea water medium tried, except in acidic ones, has this concentration of ferric phosphate or ferric citrate exhibited any inimical effects, and in neutral or slightly alkaline media it has increased the plate counts by 20 to 80 per cent or more. The addition of 0.01 per cent of either salt to 0.5 per cent peptone sea water agar gives a clear medium without filtration having a reaction of pH 7.5 to 7.6. The average plate counts of nearly a hundred samples of sea water and marine mud are between 3 and 4 per cent higher when ferric phosphate was used than when ferric citrate was used. Both yield equally reproducible results. This slight statistical advantage of ferric phosphate, together with the theoretical and possibly practical results from the phosphate enrichment of nutrient sea water media, recommends its use. Studies on a large number of pure cultures of marine bacteria to be reported elsewhere showed that the addition of ferric phosphate to various sea water media accelerated the growth and metabolism of the bacteria.

In testing the growth-promoting properties of iron in nutrient media of different pH values it was noted that iron is less stimulating as the pH decreases and is more beneficial with increasing pH, although as will be amplified below, maximum plate counts are obtained on media having a reaction of pH 7.5 to 7.8, irrespective of the presence of iron. This is illustrated by the data summarized in Table VIII which shows the average number of bacteria in twelve samples of sea water which grew on plates of nutrient sea water agar of different pH values, with and without the addition of 0.01 per cent ferric phosphate, the plate counts being expressed as ratios on a basis of the number of colonies which developed on the medium sans iron at pH 7.5 to 7.8 being 100. Further analysis of these data reveal that whereas 0.01 ferric phosphate reduced the plate count by 44.8 per cent in media at pH 5.8 to 6.0, it augmented the plate count in less acidic media from 1.9 to 123.0 per cent, the greatest stimulation occurring in the more alkaline media.

TABLE VIII

Relative Number of Bacteria which Grew on Plates of Nutrient Sea Water Agar of Different pH Values with and without the Addition of 0.01 per cent Ferric Phosphate Expressed as Ratios on a Basis of the Number of Colonies which Developed on the Medium Sans Iron at pH 7.5–7.8 Being 100. The Increase or Decrease in the Plate Count Caused by the Iron in Media of Different pH Values Is also Given Expressed as per cent

pH of medium	5.8–6.0	6.4–6.6	7.0–7.2	7.5–7.8	8.1–8.3	8.4–8.7
Growth index without iron	38	53	71	100	82	26
Growth index with iron	21	54	99	158	142	58
Percentage difference with iron	−44.8	+1.9	+39.4	+58.0	+73.2	+123.0

Lower concentrations of iron were less toxic in acidic media which suggests that the increased solubility of iron in acidic media may account for its increasing toxicity with decreasing pH. In view of the fact that 0.01 per cent of any soluble iron salt is from ten to a hundred times as much as Hotchkiss (1923) or Elvehjem (1931) have found to be tolerated by microorganisms, it is believed that marine bacteria seem to tolerate large concentrations of iron salts in sea water media only because virtually all of the iron is precipitated from solution by the phosphates, carbonates and other constituents of sea water. Additional studies will be required to elucidate the mechanism of the beneficial effects of iron salts in nutrient sea water media, but for the practical purpose of cultivating marine bacteria the use of concentrations which are theoretically toxic (0.001 to 0.01 per cent of ferric phosphate) are indicated. The foregoing observations emphasize that consistent or reproducible results are contingent more upon the pH of the sea water media than the amount of iron added.

When used in nutrient sea water media to which no iron was added, from 0.001 to 0.01 per cent of aluminum chloride stimulated the growth of marine bacteria, but not to the same extent as similar concentrations of iron salts. There was no synergetic action of aluminum and iron, the two used together producing results which were no better than when iron only was added. Low concentrations of manganese salts were also beneficial in media to which no iron salts were added, but less beneficial than either iron or aluminum. Manganese failed to fortify media which were enriched with iron or aluminum. Sea water probably contains more than enough aluminum and manganese to provide for the growth requirements of marine bacteria; the beneficial effect from the use of additional amounts of these elements probably being attributable to a catalytic or regulative function for which purpose iron is superior. According to Harvey (1939) small quantities of manganese stimulate the growth of marine diatoms.

Zinc is an indispensable nutrient for many microorganisms. It is always present in sea water although in some places only in traces (Thompson and Robinson, 1932). Since the enrichment of sea water media with varying concentrations of zinc salts failed to stimulate bacterial multiplication, it can be assumed that there is enough zinc in sea water to provide for the growth requirements of those bacteria which need it.

A lack of silica is believed by some workers to limit the growth of diatoms at certain places in the sea. It is still indeterminate if silica is required for the growth of marine bacteria but no beneficial effects followed the addition of small amounts of sodium silicate to nutrient media.

HYDROGEN ION CONCENTRATION

The pH of surface sea water ranges from 7.8 to 8.8 and decreases with depth. Very little is known concerning the hydrogen ion concentration of marine sediments but the pH of those which have been investigated at the S.I.O. ranged from 5.3 to 9.8. The pH of most of the samples of sea water whose bacteriological analysis is discussed in this paper ranged from 8.0 to 8.3; the sediments from pH 7.4 to 8.5.

If it can be assumed that the environment to which bacteria are indigenous provides conditions which are more or less optimal for the bacteria, one would expect marine bacteria to grow best at pH 8.0 to 8.3. However, early in the work it was noted that when cultivated under laboratory conditions this pH is near the upper limit tolerated by the bacteria from the sea, the maximum development occurring in nutrient sea water media at pH 7.5 to 7.8. This is illustrated by the data summarized in Figure 6 on which the average results of seven different experiments are recorded. The pH of the media was determined with glass electrodes using a Beckman pH meter.

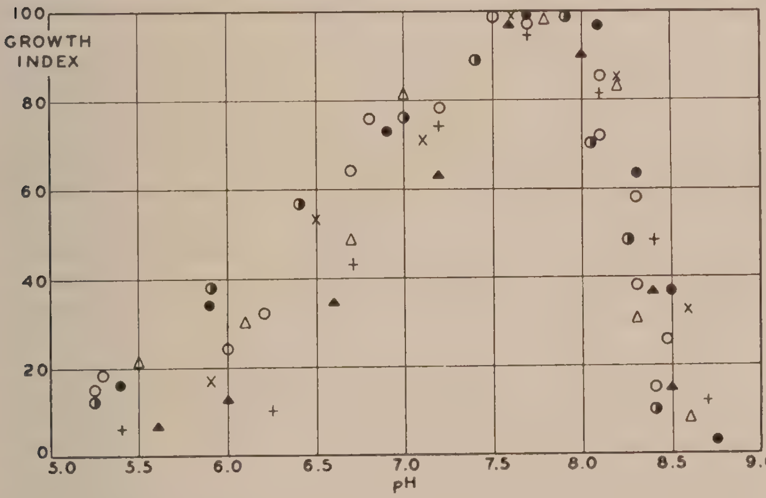

Figure 6. Effect of pH on the multiplication of marine bacteria. Circles show growth indices of bacteria in media not enriched with iron and triangles and crosses show growth indices of bacteria in media enriched with iron.

The pH of the nutrient sea water media is readily reduced to the desired level by the addition of HCl and it does not change much with autoclave sterilization, but considerable difficulty is encountered in maintaining sea water media at a high pH without materially altering its composition due to the pronounced effect of carbon dioxide on the hydrogen ion concentration of sea water and other peculiarities of its buffer mechanism (Thompson and Robinson, 1932). By depressing the ionization of hydroxyl ions the addition of a little alkali to sea water medium may result in a decrease rather than an increase in pH. The pH is increased by the addition of more alkali but in the meantime much of the calcium, magnesium, iron and perhaps other cations are precipitated from solution along with the carbonates, phosphates and maybe other anions. The precipitation of these constituents, some of which may be essential for the growth of bacteria, is accentuated by heat as during the autoclave sterilization of the media particularly if the pH exceeds 7.8. Therefore the data presented in Figure 6 do not prove that reactions alkaline to pH 8.0 are inimical to marine bacteria because the composition of the sea water has been altered in other respects. However, the data show that it is best to adjust the pH of nutrient sea water media at 7.5 to 7.8. Experiments with sea water broth sterilized by Berkefeld filtration show that most marine bacteria multiply readily in media as alkaline as pH 8.5 and some tolerate a reaction of pH 10.0–10.3 although the best growth occurred in tubes of broth having a pH around 7.6.

Our Medium 2216 consisting of 0.5 per cent Bacto-peptone, 0.01 per cent ferric phosphate and 1.5 per cent agar in sea water has a terminal reaction of pH 7.5 to 7.6 following sterilization. Unlike more basic media which take up carbon dioxide from the atmosphere and thus slowly become more acid in reaction particularly after being poured in plates, this medium undergoes very little change in reaction after it is prepared. Its buffer capacity at pH 7.5 to 7.6 is adequate to prevent much change in the reaction even from the growth of bacteria. Many marine bacteria liberate ammonium from proteinaceous substrates which would have a tendency to increase the pH but ostensibly such a change is counterbalanced by the carbon dioxide which is produced by the respiring bacteria together with that which is taken up by the medium from the atmosphere.

SUCCESSIVE DILUTION METHOD vs. PLATE COUNTS

The recorded observations of Domogalla (1932), Waksman, et al. (1933), Bere (1933) and others that plate counts detect only a small percentage of the bacteria present in water suggested the advisability of examining the possibilities of applying the successive dilution method with liquid media to the enumeration of the marine bacterial population. Theoretically, liquid medium is more suitable for the growth of water bacteria than solid medium and moreover, as elaborated by Butterfield (1933), the former is used in tubes which are easily manipulated aseptically and it makes some provisions for the simultaneous tests on the physiological characteristics of the bacteria. According to Butkewitsch (1932) the inoculation of tubes of liquid media with successive dilutions of material from the Barents Sea demonstrated the presence of from ten to a hundred times as many bacteria as plate counts on solid media.

Parallel analyses on a large number of samples of sea water and bottom sediments were made, using nutrient agar for plate counts and the successive dilution method with the identical medium without agar in test tubes. Plates were poured in duplicate, care being exercised to cool the nutrient agar to 42° C. before pouring into the plates inoculated with bacteria. The colonies which developed were counted after incubating the plates two weeks at 22° C. Following the procedure prescribed by Ziegler and Halvorson (1935) 1.0 ml. portions of each of three to five or more successive dilutions of the material differing by log one were used to inoculate the liquid medium, ten tubes being inoculated with each dilution. Thus, a minimum of thirty to fifty or more tubes were used for each sample analyzed, the number of dilutions required depending upon one's ability to estimate beforehand the order of magnitude of the bacterial population of the material being examined. With water from the open sea, which rarely contains more than a few hundred bacteria per ml. it is a matter of ease to select three effective dilutions, but with sedimentary material which may contain from less than a hundred bacteria to several million per ml., it is sometimes necessary to use eight or nine dilutions in order to insure the inoculation of the medium with three effective dilutions. Table IX shows the number of tubes inoculated with each dilution in which growth occurred within two weeks at 22° C. and the most probable number of bacteria indicated thereby according to the probability table of Halvorson and Ziegler (1933). The average number of bacteria indicated by plate counts on the same sample is also given. In order to simplify the comparison of results obtained by the two methods, only the significant figures are recorded.

A total of 38 samples were analyzed in this way, the dilution method demonstrating more bacteria in 23 of them and the plate counts being higher in the other 15 samples. The ratio of the dilution method counts to the plate counts ranged from 0.51 to 1.89; the average for the 38 samples being 1.12. In other words, the composite results show the dilution method counts to be an average of

TABLE IX

Most Probable Number of Bacteria in Samples of Marine Material Indicated by the Successive Dilution Method and the Plate Count of the Same Sample and Dilution

Sample No.	*Positive tubes in dilution*			*Successive dilution method count*	*Corresponding plate count*	*Ratio of dilution method to plate count*
	n_{10}	$n_{1.0}$	$n_{0.1}$			
1234	10	8	4	2210	1230	1.84
1235	10	10	2	3490	2120	1.64
1237	10	6	1	933	1590	0.59
1238	10	8	0	1300	1740	0.75
1314	10	7	0	1010	820	1.23
1315	10	4	2	700	370	1.89
1318	9	6	0	381	750	0.51
1319	9	8	3	499	580	0.86
1412	10	7	1	1160	690	1.68
1413	7	4	3	208	320	0.65
1432	7	4	0	171	260	0.66
1433	8	4	0	217	260	0.83
1443	10	6	0	792	630	1.26
1444	10	8	1	1500	830	1.81

12 per cent higher than the plate counts. Similarly, Butterfield (1933) found that when enough tubes were used under standardized conditions, plate counts are not markedly different from dilution method estimates of water bacteria. Ziegler and Halvorson (1935) note good agreement between plate counts and dilution method counts with some organisms but not with others, probably due to the predilection of some organisms for liquid media and others for solid media. It is believed that in most reported cases in which many times more water bacteria were demonstrated in liquid media by the dilution method than on plates of solid media, the investigators either (a) failed to use enough tubes or enough effective dilutions to get an accurate estimate of the bacterial population, (b) they were dealing with highly specialized organisms, (c) the solid medium was deficient in some property, or (d) the solid media were poured so hot that many of the thermosensitive bacteria were killed. According to Drew (1912), marine bacteria are very sensitive to temperatures as high as 40° C. and many are killed at 45° C. ZoBell and Conn (1940) report that pouring nutrient agar at temperatures exceeding 50° C. kills a large proportion of the bacteria from the sea. Working under field conditions or in an improvised laboratory on a rolling boat at sea, it is not always expeditious to cool the media to 42° C., although such treatment is prerequisite to reliable results.

During the last eight years, several different combinations of nutrients have been used to compare plate counts and successive dilution method counts. Whenever enough tubes of nearly any kind of medium tried have been inoculated with enough effective dilutions of inocula to yield reasonably reproducible results, this procedure has demonstrated the presence of very few, if any, more bacteria than equally carefully conducted plate counts. This generalization applies to the mixed heterotrophic bacterial population of sea water and marine sediments and does not apply to a few certain specific types of bacteria such as the nitrifiers, for example, which do not form colonies readily on solid media immediately following initial isolation.

In order to compare the reproducibility of results with plate counts and that of dilution method counts, a series of ten water samples were analyzed in duplicate by each method. Each of two plates of nutrient agar were inoculated with 1.0 ml. of a dilution selected to contain between 30 and 300 viable bacteria and two sets of thirty tubes of similar liquid medium were inoculated with 1.0 ml. of three effective dilutions differing by log one, each dilution being used to inoculate two sets of ten tubes. The sets of thirty were regarded as duplicates. The number of bacteria detected by both methods is recorded in Table X, which also shows the deviation of the duplicates.

TABLE X

Number of Bacteria in Wanter Samples Indicated by Duplicate Analysis by the Successive Dilution Method and Plate Count Procedures. The Deviation of Duplicates Is Expressed in per cent

	Successive Dilution Method				*Plate Count Procedure*			
Sample	*Number of bacteria*			*Per cent*	*Number of bacteria*			*Per cent*
No.	*A*	*B*	*Average*	*deviation*	*a*	*b*	*Average*	*deviation*
1701	239	310	274	25.9	263	231	247	12.9
1702	174	94	134	59.6	157	140	148	11.5
1703	197	115	156	52.5	113	120	116	6.0
1704	79	170	114	79.9	130	133	131	2.3
1705	275	334	304	19.4	263	228	245	14.3
1706	70	93	81	28.4	115	105	110	9.1
1707	101	231	166	78.3	194	163	178	17.4
1708	128	253	190	63.6	143	115	129	21.7
1709	381	116	248	106.7	225	241	233	6.8
1710	228	329	278	36.4	263	241	252	8.7

The successive dilution method indicated the presence of an average of 12.5 per cent more bacteria than the plate counts but the results show that the reproducibility of the plate counts was five times as great as that of the dilution method counts. The plate counts deviated from the mean of the two duplicates by 2.3 to 21.7 per cent, the average for the ten samples being 11.1 per cent. The successive dilution method counts deviated from the mean of the two duplicates by 19.4 to 106.7 per cent, the average for the ten samples being 55.1 per cent. Halvorson and Ziegler (1933) present theoretical considerations which show that when three effective dilutions are used to inoculate ten tubes each, the results might deviate from the modal values by 50 to 130 per cent. They conclude that over a hundred tubes would have to be inoculated with three effective dilutions in order to have the reproducibility of the results approach that commonly obtained by plating procedures.

These observations seem to warrant the conclusion that the advantage of the slightly larger number of bacteria in marine materials indicated by the successive dilution method is more than offset by its poor reproducibility except when excessively large numbers of tubes are used. The relatively large amounts of time and material ordinarily required by the successive dilution method makes it impractical except for estimating the abundance of specific types of microorganisms with differential media.

CHOICE OF A SOLIDIFYING AGENT

Rendering sea water media sufficiently solid for plate counts and other cultural purposes presents special problems. If agar is used, the media commence to congeal at 42° C. at which temperature some of the thermosensitive bacteria from the sea are killed almost instantly (ZoBell and Conn, 1940). Nutrient gelatin can be prepared so that it does not congeal until its temperature has been reduced lower than the thermal death point of any known marine bacteria but the actively proteolytic bacteria which constitute a large portion of the marine flora liquefy the gelatin causing colonies to merge before many of the slower growing bacteria have time to form macroscopically visible colonies. Sea water media can be solidified with silica gel but plate counts thus obtained do not compare favorably with those obtained with media solidified with agar. Cognizant of these difficulties Bertel (1936) has recommended the use of the skeletal material of sponges which has certain applications but it is not suitable for general plate counts and other cultural purposes. Similarly bentonite, calcium sulphate, kieselguhr, cellulose and other solidifying agents have a strictly delimited usefulness. In our quest for a general utility medium for marine bacteria comparative tests have been made on different solidifying agents.

A few preliminary tests on the available materials with which we are familiar limited the choice of a solidifying agent for nutrient media to agar or gelatin although unexpectedly good results were obtained with silica gels. When prepared with freshwater by the method outlined by Hanks and Weintraub (1936) sufficiently firm silica gels contain around 3.5 per cent of sodium chloride which is formed when the sodium silicate is neutralized with hydrochloric acid. Since sea water contains nearly this much sodium chloride, it is not surprising to find that many marine bacteria will grow in properly enriched silica gel media without the necessity of dialyzing them to remove the sodium chloride as is commonly practiced when freshwater bacteria are to be grown on silica gels. Using a procedure similar to that described by Moore (1940) it has been possible to prepare and sterilize a solution of sodium silicate which produces a suitable gel which sets slowly when mixed with a second solution containing dilute hydrochloric acid and peptone or other nutrients. These two sterile solutions are mixed and poured immediately into a Petri dish inoculated with marine bacteria. The gel sets within a few minutes but not until there has been adequate time to permit the inoculum to be mixed with the sample.

About half as many colonies develop on nutrient silica gels prepared and inoculated in this manner as on plates of nutrient sea water agar (see Table XI). The media used in the experiments summarized in Table XI all contained 0.3 per cent Bacto-peptone, 0.2 per cent proteose peptone and 0.01 per cent ferric phosphate. The colonies which developed on the nutrient silica gel medium were smaller in size and exhibited less diversity of form than those which developed on nutrient sea water agar. The superiority of the sea

TABLE XI

RELATIVE NUMBERS OR MARINE BACTERIA WHICH FORMED COLONIES ON NUTRIENT SILICA GEL MEDIUM AND CORRESPONDING NUTRIENT SEA WATER AGAR AND NUTRIENT SEA WATER GELATIN AFTER DIFFERENT PERIOD OF INCUBATION AT 22° C.

Period of incubation	*Nutrient silica gel medium*	*Nutrient sea water agar*	*Nutrient sea water gelatin*
4 days	13	38	42
7 days	22	71	63
10 days	30	89	68
14 days	37	97	—
18 days	46	100	—
24 days	54	95	—

water agar is probably attributable to the specific salt requirements of the marine bacteria rather than being due to any preference of the bacteria for agar over silica gel because from the experiments summarized in Table III it will be recalled than only 56 to 61 per cent as many marine bacteria developed in a medium prepared with 3.0 per cent sodium chloride as in that prepared with sea water, agar being the solidifying agent in both cases. However, the attempts to improve the silica gel media by adding sea water to the solutions used to prepare the silica gel have failed to yield satisfactory results to date. A heavy precipitate forms when sodium silicate is added to sea water, and while the nutrient hydrochloric acid solution can be prepared with sea water, any advantages which accrue from the increased concentration of sea salts seem to be offset by the inimical effects of the salinity of the resultant medium. Though inferior to sea water agar for general plating procedures, silica gel media prepared by the method outlined above with appropriate nutrients have proved to be useful for isolating and studying the characteristics of certain marine microorganisms. Dialyzing plates of silica gel in sea water enriched with the proper mineral salts has given excellent media for the growth of marine nitrifiers, sulphur bacteria and diatoms.

The results summarized in Table XI show that marine bacteria develop somewhat faster in nutrient sea water gelatin than in a corresponding medium prepared with agar as the solidifying agent. A total of 24 samples of raw sea water and marine sediment have been analyzed in this way and after 4 days incubation there were 11.4 per cent more colonies on the gelatin plates than on the agar plates. However, after 7 days incubation when appreciably more colonies had appeared on both media, the agar excelled and the margin of its superiority increased progressively thereafter. Gelatin liquefaction by some colonies was evident in four days and after 7 days it had become so extensive that surrounding colonies were engulfed by expanding liquefied areas. The gelatin in some plates was quite completely liquefied after 10 days incubation at 22° C. and the colonies on only those plates which were inoculated with relatively small numbers of bacteria could be counted after 14 days.

Corroborating the observations of ZoBell and Conn (1940) it was found that the number of colonies on the nutrient agar continued to increase until the maximum was reached in about 18 days although there was little difference between the counts made on the fourteenth to the twenty-fourth day. The decreasing colony count observed after the eighteenth day is due to the obliteration of small colonies by rapidly growing ones.

Three or four per cent of the bacteria from the sea on the average digest agar; a much larger proportion being found in plankton tows than in other marine materials. As a rule they do not liquefy agar as rapidly or as extensively as the proteolytic bacteria liquefy gelatin. Agar digesting bacteria usually form depressions in the nutrient agar, the diameter of the craters thus formed slowly increasing in diameter. Only infrequently is a plate of agar rendered completely uncountable by the activities of agar digesting bacteria. Angst (1929), Lundestad (1928), Waksman and Bavendamm (1931) and others have discussed the occurrence and activity of agar decomposing bacteria in the sea.

The fact that bacteria develop a little faster on nutrient gelatin than on nutrient agar during the first few days of incubation suggests that gelatin might supply some essential nutrient. According to Koser et al. (1938) gelatin is a good source of growth-promoting substances for bacteria. However, the addition of concentrations of gelatin ranging from 0.1 per cent to 1.0 per cent to nutrient agar failed to increase the plate counts or to improve results in any way.

From these experiments it is concluded that while agar is not a perfect solidifying agent for media for marine bacteria, it is better than anything else which is available. Vast differences were noted in the ease of dissolving in sea water and geling powers of different brands of agar as well as in the degree of clarity of the resulting medium. In all three respects Bacto-agar was superior. As little as 1.0 per cent of Bacto-agar is enough to render sea water medium solid enough for plate count purposes although it sets more firmly if 1.2 to 1.5 per cent is used. The concentration of agar from 1.0 to 2.0 per cent does not influence the number of colonies which develop.

ORGANIC NUTRIENTS

A survey of the literature reveals that scores of different concentrations and combinations of organic nutrients have been used for investigating the occurrence and distribution of bacteria in the sea. Peptone, beef extract, fish infusions, nutrose, gelatin, starch, dextrose and organic acids have been most extensively used constituents. The growth promoting properties of these constituents alone or in combinations including several dozen combinations specifically recommended for the multiplication of marine bacteria have been compared with our Medium 2216 consisting of 0.5 per cent Bacto-peptone, 0.01 per cent ferric phosphate and 1.5 per cent agar dissolved in sea water. Most of the media recommended by Russell (1893), Fischer (1894), Gran (1902), Drew (1911), Korinek (1926), Lipman (1926), Lloyd (1930), Levine and Schoenlein (1930), Bavendamm (1932), Gee (1932), Bedford (1933), Benecke (1933), Reuszer (1933) and Waksman et al. (1933) for the growth of marine bacteria as well as various modifications have been tested. In the interests of the economy of space may it suffice to state that without exception all were found to be inferior to Medium 2216, there being only from 2 to 86 per cent as many bacteria growing on them as on Medium 2216 and, in general, fewer species.

One of the best media tried was one recommended by Reuszer (1933) and used by Waksman et al. (1933), Renn (1940) and others at the Woods Hole Oceanographic Institution. It consists of 0.1 per cent each of peptone and dextrose, 0.005 per cent K_2HPO_4 and 1.5 per cent agar dissolved in sea water. In a large number of comparisons it was found that only from 53 to 78 per cent as many colonies developed on this medium after different periods of incubations as on our formula 2216. Upon the addition of 0.01 per cent ferric phosphate to Reuszer's formula it gave plate counts which were an average of 86 per cent as high as those obtained on Medium 2216.

The effect of dextrose and the concentration of peptone on plate counts is illustrated by the data summarized in Table XII. The best results were obtained on media containing around 0.5 per cent Bacto-peptone. Dextrose is beneficial if the concentration of peptone is low but no advantages were noted for the use of dextrose in media containing as much as 0.5 per cent peptone. There is much more tendency for the colonies to be mucoid or to spread with subsequent merging on media containing more than 0.5 per cent peptone or on that enriched with glucose.

TABLE XII

Comparative Plate Counts on Ferric Phosphate Sea Water Agar Prepared with Different Concentrations of Bacto-peptone without and with 0.1 per cent Dextrose

Medium	*Plate count without dextrose*	*Plate count with dextrose*
0.10 per cent peptone	72	86
0.25 per cent peptone	87	90
0.50 per cent peptone	100	102
1.0 per cent peptone	93	94
2.0 per cent peptone	96	91
Reuszer's medium (No Fe)	—	69

Some of the media used in the work of ZoBell et al. (1933, 1936, 1940) have been enriched with proteose-peptone, neopeptone, tryptone or beef extract on the theory that these substances might favor the growth of certain fastidious organisms. While either alone or in combination with Bacto-peptone these substances have proved to be useful for the cultivation of pure cultures, our extensive experiments indicate the use of none of them for obtaining the maximum development of colonies (total numbers as well as kinds). In concentrations not exceeding 1.0 per cent they are not inimical except that beef extract imparts an undesirable brownish color to the medium.

Starch, glycerol, mannitol, citrates, lactates, succinates and malates have been recommended for the enrichment of media for the growth of marine bacteria by certain workers. The addition of from 0.1 to 1.0 per cent of the compounds to Medium 2216 has not improved it although studies on pure cultures to be reported elsewhere show that these compounds are utilized by certain bacteria and they are most useful constituents of differential media.

The work of Ostroff and Henry (1939) with pure cultures proves that marine bacteria are not fastidious in their carbon or nitrogen requirements. Some of their cultures could utilize as many as 14 of 21 different nitrogen compounds investigated and most of the bacteria grew luxuriantly on amino acids; glutamic acid, aspartic acid and asparagine being best in the order named. It was not within the scope of their work to try peptone which is a mixture of many amino acids and other nitrogen compounds. We find that neither glutamic acid, aspartic acid nor asparagine is as good as peptone for the cultivation of the general marine bacterial population. The enrichment of peptone media with 0.01 per cent of these amino acids either alone or in combination did not improve it for plate count purposes.

Snow and Fred (1926) found sodium caseinate agar to be superior to any other medium they tried for the cultivation of freshwater bacteria. Other workers have recommended the use of nutrose or sodium caseinate either with or without additional nutrients for the cultivation of marine or fresh water bacteria. The results which we obtained with the use of sodium caseinate and Bacto-nutritive caseinate are summarized in Table XIII. The average plate counts of four samples of sea water and three of marine sediments are given expressed as ratios on a basis of the plate count on Medium 2216 being 100. From the table it will be noted that only about half as many colonies appeared on the sodium caseinate media as on the peptone medium and those which did appear were much smaller and developed slower. The Bacto-nutritive caseinate was inferior to sodium caseinate in these tests. Many colonies on the caseinate medium might have escaped detection due to their small size and the opaque-

TABLE XIII

Comparative Number of Marine Bacteria which Formed Colonies on Sea Water Iron Agar Enriched with Various Nutrients after Different Periods of Incubation at 22° C.

Nutrients	*Comparative plate count after*	
	7 days	*14 days*
0.2% sodium caseinate	19	46
0.5% sodium caseinate	32	53
1.0% sodium caseinate	37	54
0.2% sodium caseinate + 0.5% peptone	51	68
0.5% sodium caseinate + 0.5% peptone	56	71
1.0% sodium caseinate + 0.5% peptone	38	49
0.2% nutritive caseinate	15	23
0.5% nutritive caseinate	19	32
1.0% nutritive caseinate	20	38
0.5% peptone (Medium 2216)	86	100

ness of the media. The opaqueness of the media is also largely responsible for the fact that not as many colonies were found on the caseinate media enriched with peptone as on the peptone medium although it is not improbable that the mineral balance of the sea water was disrupted by the caseinate precipitating certain ions. The plate counts on the peptone medium were much more closely reproducible than on the caseinate media as indicated by the agreement of duplicates.

Considerable difficulty was encountered in trying to obtain reproducible results with various fish and seaweed infusions. In no case did any of four different fish and mollusk infusions or extracts either with or without peptone yield plate counts which were as large as those obtained without the infusions or extracts. Fish bouillon agar prepared with sea water according to the methods of Fischer (1894) was decidedly inferior to our standard peptone agar. Negative results were likewise obtained with the extracts prepared from two different red algae and three brown ones. Similarly after trying the extracts from marine organisms Lloyd (1930) concluded that they are not essential for the growth of marine bacteria in spite of the claims of many earlier workers.

The recent reviews of Koser and Saunders (1938) and Janke (1939) stress the importance of accessory growth factors, many of which are organic in nature, for the multiplication and metabolism of microorganisms. Harmsen and Verweel (1936) and others have recommended the enrichment of plating media with growth-promoting substances such as yeast extract or soil extract. The unpublished observations of Michener and others in the S.I.O. laboratory indicate that marine bacteria require certain accessory growth substances similar to those required by terrestrial and fresh water bacteria but apparently there is enough in sea water to initiate the growth of marine bacteria. Traces of nicotinic acid, thiamin chloride, pantothenic acid, indolacetic acid and yeast extract added to our ferric phosphate peptone Medium 2216 have not increased the plate counts although as will be reported elsewhere, some of these substances are beneficial for the growth of pure cultures in synthetic media.

SUMMARY

Most of the bacteria recovered from sea water as well as bottom sediments at places remote from possibilities of terrigenous contamination have specific salt requirements which are satisfied best by natural sea water. Neither synthetic sea water nor other isotonic salt solutions are satisfactory substitutes. Merely diluting sea water with fresh water materially reduces the number of marine bacteria which will grow in it. Conversely very few terrestrial or freshwater bacteria are able to grow in nutrient sea water media upon initial isolation.

There is no evidence that the addition of nitrate to nutrient sea water media as has been recommended by others is beneficial, and concentrations exceeding 0.1 per cent potassium nitrate are inhibitory.

There are indications for the addition of 0.01 per cent dibasic potassium phosphate to peptone sea water media although it normally contains sufficient phosphate to provide for the multiplication of marine bacteria.

The enrichment of nutrient sea water media with a trace of iron increases plate counts 18 to 76 per cent, 0.01 per cent ferric citrate or ferric phosphate being almost equally beneficial. The use of the latter is recommended because it provides for the phosphate requirements as well as the iron. This concentration of iron in sea water is toxic only when the medium is acid in reaction.

Marine bacteria appear to grow best in media having a pH of 7.5 to 7.8 although sea water *in situ* is usually somewhat more alkaline than this.

Successive dilution method counts using tubes of nutrient sea water broth demonstrated the presence of 12 per cent more bacteria than plate counts on comparable nutrient sea water agar but the latter yielded much more reproducible results and require much less medium and time.

A comparative study of the merits of different solidifying agents

recommends the use of 1.2 to 1.5 per cent Bacto-agar as the best for plating media. Gelatin is liquefied too rapidly by marine bacteria to be satisfactory and although silica gel prepared by a simplified method has certain advantages, it does not give results as good as agar for the demonstration of the heterotrophic bacterial population.

The use of various algae and fish infusions, carbohydrates, organic acids, nitrogen compounds and other organic nutrients in different concentrations and combinations have not proved to be as good as Bacto-peptone for the growth of marine bacteria as indicated by the number and kinds of bacteria on plates as well as the reproducibility of plate counts.

Although special media are required for certain groups of organisms and for special purposes, for maximum plate counts and for the cultivation of most aerobic heterotrophic marine bacteria Medium 2216 is recommended. It contains 0.5 per cent Bacto-peptone, 0.01 per cent ferric phosphate and 1.5 per cent Bacto-agar dissolved in aged sea water, the pH being around 7.6 after autoclave sterilization.

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THE ESTIMATION OF A QUOTIENT WHEN THE DENOMINATOR IS NORMALLY DISTRIBUTED

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1. Introduction. In an oceanographic investigation we have to deal with a time series consisting of single pairs of observed values x, y, of two independent stochastic variables, whose true (mean) values we shall denote respectively by a, b. Of interest is the corresponding time series of quotients (b/a), which it is required to estimate from the observations x, y. Both x and y are approximately normally distributed about their mean values a, b with rather large variances σ_x^2, σ_y^2 which can be estimated. It is easily possible for x to vanish or even to be of opposite sign to a, although a cannot itself vanish. The required estimates of (b/a) should have the property that they can be numerically integrated, i.e. that an arbitrary sum of such estimates shall equal the corresponding estimate of the true sum.

Let us define a function $\gamma(x)$ to have the property that its mathematical expectation $E\{\gamma(x)\}$ is exactly $1/a$, where $a = E(x)$. If such a function exists we shall have

$$E\{y \cdot \gamma(x)\} = E(y) \cdot E\{\gamma(x)\} = b \cdot (1/a) = b/a \tag{1}$$

so that $y \cdot \gamma(x)$ will be an estimate of b/a which has the required property: namely such estimates can be added, and we have

$$E\{y_1\gamma(x_1) + y_2\gamma(x_2)\} = E\{y_1\gamma(x_1)\} + E\{y_2\gamma(x_2)\} = b_1/a_1 + b_2/a_2$$

as required. It turns out that if x is normally distributed with non-zero mean such a function $\gamma(x)$ does exist, and is given by the formula

$$\gamma(x) = \frac{1}{\sigma_x} \exp\,(x^2/2\sigma_x^2) \int_{x/\sigma_x}^{\infty} e^{-t^2/2}\,dt = \frac{1}{\sigma_x} R_{x/\sigma_x} \tag{2}$$

where R_u is the "ratio of the area to the bounding ordinate" which is tabulated by J. P. Mills,[1] also in Pearson's tables.[2] Equation (2) holds if a is positive; if a is negative the integration should extend over $(x/\sigma_x, -\infty)$. It is easy to verify that

$$E(\gamma(x)) = \frac{1}{\sqrt{2\pi}\,\sigma_x} \int_{-\infty}^{\infty} \gamma(x) \exp\left(-\frac{(x-a)^2}{2\sigma_x^2}\right) dx = \frac{1}{a} \tag{3}$$

by direct substitution from (2).

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[1] J. P. Mills, "Table of ratio: area to bounding ordinate, for any portion of the normal curve," *Biometrika*, Vol. 18 (1926), pp. 395–400.

[2] Karl Pearson, *Tables for Statisticians and Biometricians*, part II, table III, Cambridge Univ. Press.

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2. The law of large numbers for $\gamma(x)$. The function $\gamma(x)$ defined by (2) has mean value $1/a$ as required, but its second moment (hence variance) does not exist, as may readily be verified. By a theorem of Khinchine[3] however, its values satisfy a law of large numbers. It will be of interest to inquire about the "strength" of this law of large numbers for $\gamma(x)$. Namely, given a positive number ϵ, how many "observations" (independent estimates) $\gamma(x)$ will suffice to guarantee probabilities of .50, .90, .95, etc. for the following inequality to hold

$$\left| \frac{\gamma(x_1) + \gamma(x_2) + \cdots + \gamma(x_n)}{n} - \frac{1}{a} \right| < \epsilon \tag{4}$$

where n is the number of "observations."

In order to arrive at a rough answer to this question we have made use of certain inequalities due to Tshebysheff (Tshebysheff's "method of moments", cf. Uspensky[4]). Let u be an arbitrary stochastic variable whose distribution has moments of the first and second order which are known. Denote by m its first moment, by σ^2 its variance, then it results from Tshebysheff's theory that the probability $P(u_1, u_2)$ for a value of u to lie between u_1 and u_2 (i.e. $u_1 \leqq u \leqq u_2$) satisfies the inequality

$$P(u_1, u_2) > 1 - \frac{\sigma^2}{(u_1 - m)^2 + \sigma^2} - \frac{\sigma^2}{(u_2 - m)^2 + \sigma^2}. \tag{5}$$

This inequality is independent of the values, or even the existence, of further moments of the u-distribution beyond the second, and depends only on the condition that the cumulant of the distribution function shall have at least three "points of increase."

Although $\gamma(x)$ does not have a second moment, a second moment does exist for those values of $\gamma(x)$ which correspond to $x \geqq -\theta > -\infty$, where θ is an arbitrary number, positive or negative. If we can estimate the first two moments of $\gamma(x) \sim 1/x$ corresponding to a given value of θ, then for a given number n of observations we need only to divide the corresponding variance by n to obtain σ^2 in (5), then multiply (5) by the nth power of the (normal) probability for the inequality $x \geqq -\theta$, in order to obtain a lower bound for the probability of the inequality (4). θ is to be determined so as to yield a maximum result.

The first moment m_1 of $\gamma(x)$ for values of $x \geqq -\theta$ is easily computed, and is given by the formula

$$\sigma_x m_1(\theta) = \frac{\sigma_x}{a} \left\{ 1 - \frac{R_{-\theta/\sigma_x}}{R_{-(\theta+a)/\sigma_x}} \right\}. \tag{6}$$

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[3] J. V. Uspensky, *Introduction to Mathematical Probability*, pp. 195, McGraw-Hill (1937).

[4] J. V. Uspensky, l.c. pp. 365 ff.

The second moment is harder to compute, but if we place

$$\phi(\theta) = K\cdot(m_2 - m_1^2) = \frac{1}{\sqrt{2\pi}\,\sigma_x}\int_{-\theta}^{\infty}[\gamma(x)]^2 \exp\left(-\frac{(x-a)^2}{2\sigma_x^2}\right)dx \tag{7}$$

$$-\frac{\left[\int_{-\theta}^{\infty}\gamma(x)\exp\left(-\frac{(x-a)^2}{2\sigma_x^2}\right)dx\right]^2}{\sqrt{2\pi}\,\sigma_x\int_{-\theta}^{\infty}\exp\left(-\frac{(x-a)^2}{2\sigma_x^2}\right)dx}$$

where

$$K = \frac{1}{\sqrt{2\pi}\,\sigma_x}\int_{-\theta}^{\infty}\exp\left(-\frac{(x-a)^2}{2\sigma_x^2}\right)dx = \frac{1}{\sqrt{2\pi}}\int_{-(\theta+a)/\sigma_x}^{\infty} e^{-t^2/2}\,dt$$

we easily obtain the relationship

$$\phi'(\theta) = \frac{1}{\sqrt{2\pi}\,\sigma_x^3}\exp\left(-\frac{(\theta+a)^2}{2\sigma_x^2}\right)\left\{R_{(-\theta/\sigma_x)} - \frac{\sigma_x}{a}\left(1 - \frac{R_{-\theta/\sigma_x}}{R_{-(\theta+a)/\sigma_x}}\right)\right\}^2. \tag{8}$$

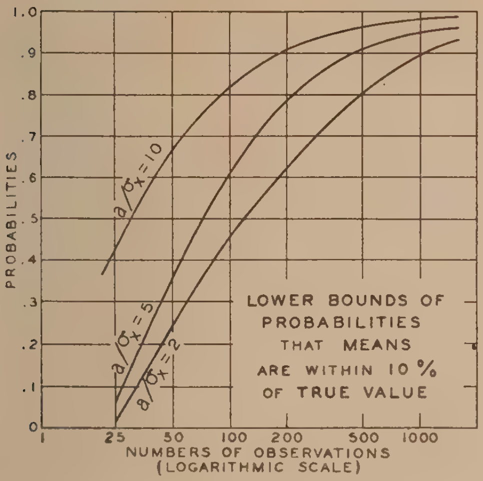

FIG. 1

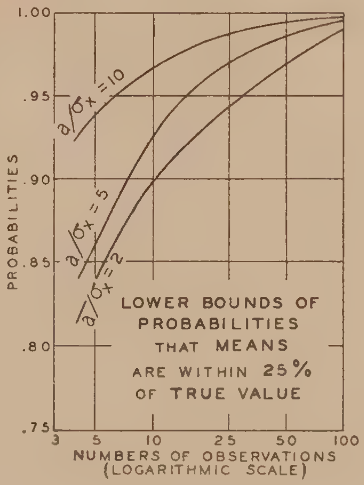

FIG. 2

From (7), using a table of the probability integral, it can be verified that $\phi(-a - 3\sigma_x) \ll 0.001$. Assume, therefore, as a boundary condition $\phi(-a - 3\sigma_x) = 0$ then (8) can be integrated graphically or numerically. It is by this means that the curves shown in Figs. 1 and 2 were determined. Computations were also attempted for $a/\sigma_x = \frac{1}{2}$, $a/\sigma_x = 1$, but it was not possible to obtain significant results: it would be necessary in these cases to take more than two moments into account, which would lead to hopeless complications. In these figures the ordinates represent probabilities for an observation to fall between *.90a* and *1.11a* (Figure 1), and between *.75a* and *1.33a* (Figure 2), respectively.

3. Two practical formulas for computations. It seems worthwhile to note here two simple formulas in connection with Mills' ratio (2) which will be useful for computations. The first is the obvious relationship

$$R_{-u} = \sqrt{2\pi}\, e^{u^2/2} - R_u = 1/z - R_u \tag{9}$$

in the notation of Pearson's tables. The second applies to large values of x, and may be written

$$\frac{x}{x^2 + \sigma_x^2} < \gamma(x) = \frac{1}{\sigma_x} R_{x/\sigma_x} < \frac{1}{x} \tag{10}$$

(10) is true for $x > 0$, and can be proved by means of the differential equation which $\gamma(x)$ satisfies.

4. Remarks. The estimate $\gamma(x)$ has the following inadequacy: If only a single observation x is known, then it is unknown whether a is of like or unlike sign compared to x. It turns out then that the mathematical expectation for the value of $\gamma(x)$ vanishes identically. This difficulty of course disappears if more than one observation is available. Methods of avoiding this difficulty for time series, e.g. by noting relative frequencies for observations separated by 1, 2, 3 etc. intervals to agree in sign, will be discussed elsewhere in connection with practical applications.

It may be worthwhile to note that Geary[5] developed certain characteristics of the distribution of a quotient, which however are not adapted to our purposes.

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[5] Geary, R. C., "The Frequency Distribution of a Quotient," *Jour. Roy. Stat. Soc.*, Vol. 93 (1930), pp. 442–446.

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RIP CURRENTS: A PROCESS OF GEOLOGICAL IMPORTANCE[1]

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ABSTRACT

Rip currents are defined as seaward-moving streaks of water which return the water carried landward by waves. These currents are believed to be an almost universal accompaniment of large waves breaking on an exposed coast.

Unlike the largely hypothetical undertow, rip currents flow principally at and near the surface. They attain velocities up to at least 2 miles an hour and extend on occasions for 1,000 feet or more from the shore. Geologically the currents are of importance, since they carry a suspended load of fine sediment out from the shore. Small channels in the sand are produced by the flow in the near-shore portions of the rip currents. The development and changes of these channels have been investigated. The strong outflow of the current and the presence of the channels along the bottom constitute a serious danger to inexperienced swimmers.

INTRODUCTION

The observation that a stick thrown into the breakers from a beach will usually return to the shore demonstrates that surface water is carried landward in the breaker zone in the absence of an offshore wind. Floating objects seaward of the breaker zone are also observed to move toward land but at a slower rate. Thus objects thrown into the sea at the end of the 1,000-foot Scripps pier (Fig. 1) almost invariably move shoreward, although their movement usually has a longshore component. A return flow required by this landward movement has led to the idea that the water returns beneath the surface. The popular idea of violent undertow which is said to pull bathers beneath the surface was first challenged by W. M. Davis,[2] and a considerable discussion of the subject ensued. Conflicting evidence was presented, centered chiefly on whether bathers were dragged out from the beaches or whether the waves had as much forward as backward transport.[3]

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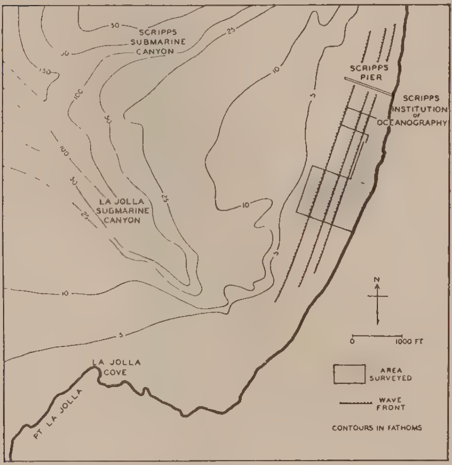
50
SCRIPPS SUBMARINE CANYON
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LA JOLLA SUBMARINE CANYON
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LA JOLLA COVE
PT LA JOLLA
AREA SURVEYED
WAVE FRONT
CONTOURS IN FATHOMS

FIG. 1.—Showing the area in which most of the investigations were undertaken. Nature of sea floor shown by contours.

After discussing with lifeguards the causes for surf rescues and making some preliminary observations along the beaches, Shepard[4] called attention to definite evidence of outward drag of swimmers in relatively narrow seaward-moving belts of water. These lanes of agitated water extending out at right angles to the beach are well known to lifeguards and to experienced swimmers but seem to have largely escaped the notice of scientists. They are known as "rip tides" or "sea pusses," but the name "rip current" was proposed as being more appropriate, and the term "rip" might also be used as an abbreviation, which removes the unfortunate tidal connotation of the popular term "rip tide."

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[2] "The 'Undertow,'" *Science*, Vol. LXII (new ser., 1925), pp. 206–8.

[3] Walter C. Jones, "The Undertow Myth," *Science*, Vol. LXI (new ser., 1925), p. 444; Wallace Craig, "The 'Undertow,'" *Science*, Vol. LXII (new ser., 1925), p. 30; I. Brant, "The 'Undertow,'" *Science*, Vol. LXII (new ser., 1925), pp. 30–31; Davis, "The Undertow Myth," *Science*, Vol. LXII (new ser., 1925), p. 33.

[4] "Undertow, Rip Tides or Rip Currents," *Science*, Vol. LXXXIV (new ser., 1936), pp. 181–82.

These rip currents were described as moving outward both at the surface and underneath the surface, so that they are something quite distinct from the supposed undertow. Subsequently, O. F. Evans,[5] on the basis of observations with colored water in lakes, showed that with an onshore breeze water may move shoreward at the surface and return underneath, thus suggesting the reality of undertow under conditions of an onshore wind. Evans' suggestion that such subsurface-return currents, while inconsequential in his experiments, might attain dangerous proportions, led to observations by Shepard and La Fond[6] which showed that at the Scripps Institution pier during strong onshore winds no appreciable undertow could be discerned but that the water moved principally alongshore both at the surface and near the bottom. Observations made by the writers subsequently have failed to produce any confirmation of the idea of dangerous undertow. While slow outward-moving subsurface currents may exist, the chief seaward return of water moved in by the waves seems to be in the form of rip currents.[7]

Recent investigations of the rips have shown that they are, in all probability, a phenomenon associated with all coasts where surf comes in more or less directly onto the shore. Surveys initiated recently by Emery have shown the erosional effects of these currents in shallow water. All the authors have combined in surveys to determine the nature of water movement in the rip currents. Also records compiled over several years by La Fond, Shepard, and others have been analyzed to find the relation of rip currents to other phenomena. The present report is an attempt to summarize the information obtained by these studies.

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[5] "Undertow," *Science*, Vol. LXXXVIII (new ser., 1938), pp. 279–81.

[6] "Undertow," *Science*, Vol. LXXXIX (new ser., 1939), pp. 78–79.

[7] In an article to appear shortly in *Science*, O. F. Evans refers to undertow as a subsurface drift in various directions both landward and away from the land but in a direction opposite to the drift at the surface and existing at some distance from the shore. The existence of an undertow of this nature is not denied by the present writers. On the contrary, evidence could be supplied to show such counterposed drifts in the La Jolla district, although for the most part in directions alongshore. The writers have used undertow in the popular sense of a dangerous, subsurface current moving out from the shore under the oncoming waves.

GENERAL DESCRIPTION OF RIP CURRENTS

SURFACE MANIFESTATIONS

Rip currents, like double rainbows or sun dogs, are phenomena which are not seen by casual observers until they have been pointed out by someone familiar with them. However, after their characteristics are known, they can be easily recognized along shorelines where large breakers form. Rips are most readily identified by an observer looking down from an elevation, but careful scrutiny from the beach will also serve to show their presence. The following are their chief characteristics:

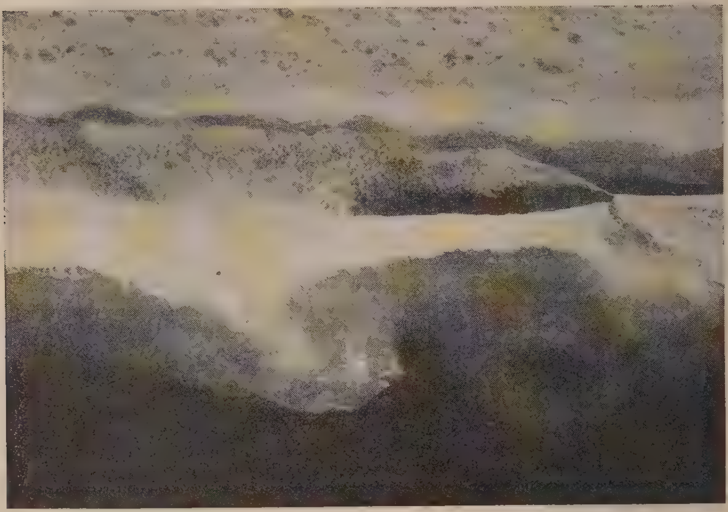

FIG. 2.—Showing a rip current extending out from the beach at Coronado, California. Note portions of other less pronounced rips on either side. Official United States Navy photograph.

1. *Sediment-laden water.*—Rip currents located off a shore containing relatively fine sand or silt can be identified by a brown streak of water which protrudes beyond the breaker zone. This brown color is due to the sediment suspended in the water by the breaking waves and dragged seaward in the rip current. These brown streaks can be seen to move seaward spreading out as they go. New belts join them from time to time (Fig. 2).

2. *Green water.*—Shoreward of the main breaker belt one can often see a zone where the water has a distinctly greenish appearance. This color is due to the greater depth generally found along the course of a rip current. As will be shown later, the trend of these inner channels is likely to be diagonal to the shoreline.

3. *Foam belts.*—Where the bottom is rocky, so that the rip currents do not contain brown water, their presence may be observed by bands of foam which project seaward from the breaker belt (Fig. 3). Foam is also associated with the brown water and is often confined to the outer rim of an advancing rip.

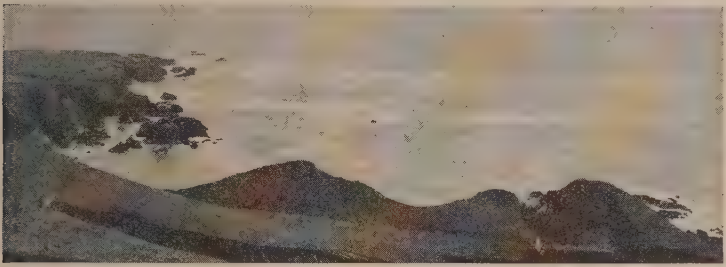

FIG. 3.—Showing a rip current indicated by foam extending out from a rocky point without any beach.

4. *Agitated water.*—In a rip current the surface of the water is usually very much agitated, resembling in appearance a tidal current moving against oncoming waves. This agitation cannot only be seen but can be heard and felt both by a swimmer and by an oarsman rowing through the outer tongue of a rip current. Beyond the breakers the irregular waves in the rip sometimes have the appearance of whitecaps. According to reports of lifeguards, the water in a rip may be so choppy as to make breathing very difficult.

5. *Gap in advancing breakers.*—While waves do break in the rip-current zones, they often break much nearer shore than on either side, so that it is a common thing to see an advancing breaker with a gap at the point where the rip current is moving seaward (Fig. 4). However, a gap in the breakers does not necessarily show the presence of a rip current, since it may be due to a greater depth of the water along a belt where no rip current is operating or to interference of waves.

6. *Seaward movement of floating objects.*—When one is in doubt concerning the reality of a supposed rip current, drifting objects will often serve to test the case. For example, the existence of a rip was established where a stick floated out from the base of a 20-foot rock cliff directly against a storm wind and against large waves. Possibly such occurrences are common but have not been observed because no one would suspect the presence of an outward-moving surface current at such a place. The drift of objects in typical rip currents will be discussed below.

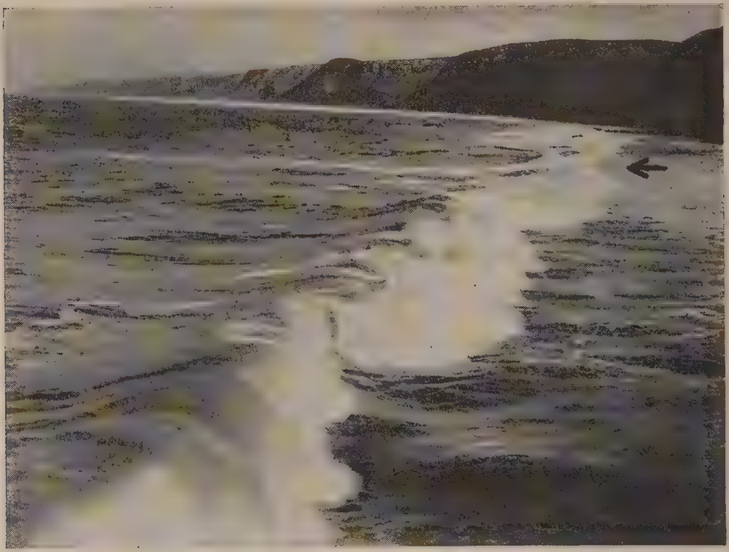

FIG. 4.—Showing the gap in an advancing wave crest where a rip current is moving seaward.

WIDTH AND OUTWARD EXTENT

The maximum width and outward extent of rip currents cannot be determined until more data are available. Estimates made at Venice, California, by Mr. C. P. L. Nicholls[8] limited the outward projections to about $\frac{1}{2}$ mile. At La Jolla a convenient index is provided by the 1,000-foot Scripps pier. It is not unusual for a rip to extend beyond the end of this pier, and on some occasions they appeared to extend more than twice that distance from shore. From the cliffs along the San Simeon–Carmel coast highway, observations of rip currents suggested an outward extent of about a half-mile, under what were probably typical wave conditions. Since average wave conditions at La Jolla are accompanied by relatively short rip currents and large waves by greatly extended rips, it might be supposed that considerably greater lengths would accompany exceptionally large waves in this exposed San Simeon–Carmel area.

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[8] Supervisor of aquatics of the Los Angeles department of playground and recreation.

Rip currents are narrow near shore, commonly not over 50–100 feet across, but they widen farther from shore. Off La Jolla, beyond the breakers, they have been measured as being from 100 to 440 feet across. In the widest of these rips the current was especially concentrated in a belt 180 feet across. The rip currents observed from the San Simeon–Carmel highway appeared to have greater width compared to length than those seen at La Jolla or off other sandy beaches. The former were probably over 1,000 feet across. It was noted that all the currents are sufficiently narrow near shore so that swimming out of them should not be difficult, but a longer swim would be required beyond the breaker belt. However, currents in the outer zones are not so strong.

RELATION TO COASTAL AND SHORELINE CONFIGURATION

The statements from lifeguards regarding rip currents refer exclusively to areas where there are long, relatively straight beaches such as the one south of Scripps Institution (Fig. 1). However, investigation has shown that the currents are by no means confined to shores of this type. As far as could be determined, rip currents are found off all types of coasts where waves pound in more or less directly against the shore.

Relation to indentations.—Rip currents are found in many cases off the center of small beach indentations. In rare cases these indentations are reported to be the result of drains entering the sea at that point, but in general they are due to natural causes and processes which allow them to shift in position. Rips are also observed in larger coastal indentations. In the cases where there is no prevailing longshore current, they generally move out at the center of the indentation, or they form on the downcurrent side of the bay where strong drifts exist.

At La Jolla Cove (Fig. 1) large waves do not ordinarily occur, but under some conditions resonance or some type of interference causes the building-up of a series of large waves, and these waves sweep into the cove with great force. After a series of waves of this type, a current is observed moving out from the rocky point which lies east of the cove.

Relation to rocky coasts.—An example has been referred to previously (Fig. 3) where a rip developed off a rocky coast where there was no beach. Other cases were observed along the mountainous coast of the San Simeon–Carmel highway. There are also a few rips off the rocky cliffs of Point Loma near San Diego. However, it is likely that rips are less common on rocky coasts than off sand beaches. Examination of the two types on the same day revealed fewer rips off the rocks. On the other hand, it should be borne in mind that it is not easy to recognize the rips where there is no bottom sediment to be thrown into suspension to indicate the outward movement beyond the breakers.

Relation to artificial structures.—Rip currents are frequently found running seaward along piers and groins. The slight deflecting influence of a pier evidently plays an important part in localizing these currents. At many beaches guards have posted warnings for bathers to avoid the vicinity of these structures largely because of the dangerous rips.

NATURE OF CURRENTS

Surface movement.—Investigations at La Jolla have given some information concerning the movement of water particles in what appear to be typical rip currents. Conversations with lifeguards have confirmed these observations. Figure 5 gives what is believed to represent typical movement of water in one of these rip currents. It can be seen to consist of three main parts, which have been called the "feeders," the "neck," and the "head." Just outside the beach there is a flow of water nearly parallel to the shore. An object drifting in this feeder current is carried in a path diagonal to the shore into the main outward-flowing current, or the neck, which moves essentially at right angles to the general coastal trend. Ordinarily the water coming into the neck enters from a feeder on either side, although one current may flow more swiftly than the other. In these feeders, currents have been observed to move at about 2 miles an hour, although higher velocities may exist during storm waves. Water enters the neck not only from the feeders but also to some extent from the sides farther out.

In the inner portion of the neck, shoreward of the point where the large waves break, current velocities are high, but the current becomes more intermittent in character because of the effects of the breaking waves. With each advancing wave the outmoving current is checked or may be given a strong side motion. After the crest has passed, the outward flow is resumed. In the outer portion of the neck the counteracting effect of large breakers is particularly noticeable. Frequently the forward surge of the waves completely interferes with the seaward passage of a floating object which simply moves back and forth until it is thrown out of the rip by a lateral movement of the current. As will be shown subsequently, this is the most dangerous position for a swimmer, particularly if he is trying to get out of the neck on the side from which the main current is moving (Fig. 5). According to Mr. T. V. Warren,[9] the currents may enter the neck

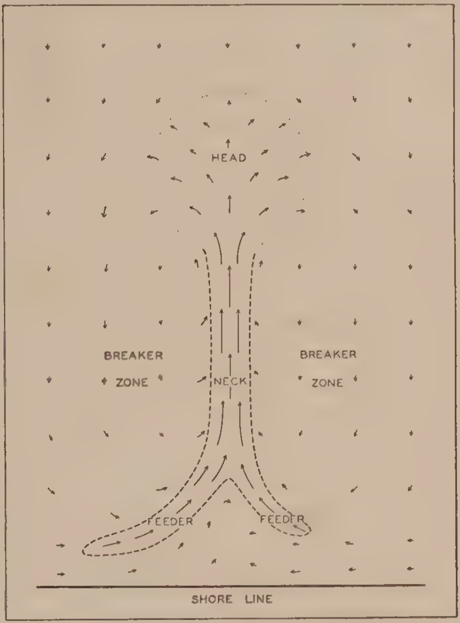

Fig. 5.—Diagrammatic sketch of a rip current showing its component parts and the common association of currents with it.

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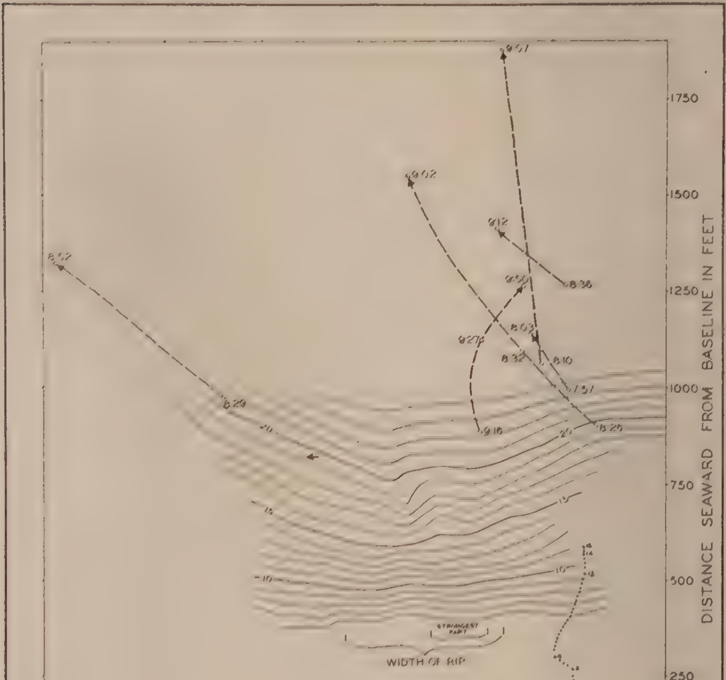
[9] A lieutenant in the Los Angeles County Lifeguards, who has had twenty years of experience with rip currents.

from both sides so that a floating object may be held within the neck until a pause in the onslaught of the breakers allows it to move outward. Also, on two occasions it was observed that, with small,


9.07
9.02
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9.27
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9.16
8.25
20
15
10
0
STRINGEST PART
WIDTH OF RIP
1750
1500
1250
1000
750
500
250
0
DISTANCE SEAWARD FROM BASELINE IN FEET
3000
2750
2500
2250
2000
1750
1500
DISTANCE SOUTH OF SCRIPPS PIER IN FEET

FIG. 6.—Showing the direction and speed of floating objects observed in rip currents south of the Scripps Institution pier. Shows also the contours of the bottom determined subsequently from the same area and during times of strong rip currents. The near-shore channel was surveyed on the day subsequent to the survey of the outer portion. Dotted line shows motion of a float submerged 2 feet below the surface. Time refers to clock time for the surface objects and to minutes from start in the case of the float. Contour interval 1 foot. Soundings are reduced to mean lower low water.

short-period waves accompanying an onshore wind, floating objects moved through the breakers without much delay.

A floating object which is thrown out of the rip at the neck moves shoreward and then is caught by one of the feeders and carried seaward once more. In moving seaward the path weaves back and forth under the influence of the oncoming breakers. A piece of kelp may describe several circles before being carried up onto the beach or carried seaward through the neck. Lieutenant Warren informed the writers of cases where lifeguards in making a rescue had also been forced into the same circular path, so that they went through the rip several times before making their escape.

In the outer portion or head of the rip current the water spreads out, and the rip becomes much wider (Fig. 5). Observations of the surface currents in the head were made from rowboats in the vicinity of the Scripps Institution pier. Paths of floating objects, both on the sides of rip currents and within them were plotted (Fig. 6). It will be noted that the general direction of movement was outward, but ample evidence of longshore movement away from the rip was seen on either side of the main current. At a distance of about 900 feet from the shore an outward movement of $\frac{1}{2}$ mile an hour was observed. Other objects moved outward respectively at $\frac{1}{3}$ and $\frac{1}{5}$ of a mile an hour.

To find the lateral extent of the rip, three objects were set adrift over a width of 350 feet along a line about 900 feet from the shore. Only one of these was thought to be definitely in a rip current, but all of them drifted outward, showing that the effect of the rip was much more widespread than was supposed. Another object set out on the south side of the head of a rip current was observed to move southward at first. Returning to the locality after observing other floating objects, we were unable to find the south-drifting float. Later it was picked up on the beach about 400 feet south of where it had been set out. Presumably it had described an arc and turned toward shore.

Along the side of an advancing head, eddies are often observable (Fig. 7). These whirls turn to the right on the right side of the rip and to the left on the left side. A turning movement is also experienced in a rowboat allowed to drift in the advancing end of a rip current.

Subsurface movement.—The movement of currents beneath the surface has not yet been completely explored either in rip currents or in breaker zones on either side. According to Lieutenant Warren, the flow may be stronger either at the surface or underneath. It is his observation that where the neck is very narrow the flow underneath is stronger than at the surface and where the rip is spread over considerable area the flow decreases with depth. The presence of gullies in the sand (to be described later) underneath the feeders and the neck testify to swift movement where the rip is confined. Also observations from the Scripps pier[10] showed that rip currents,

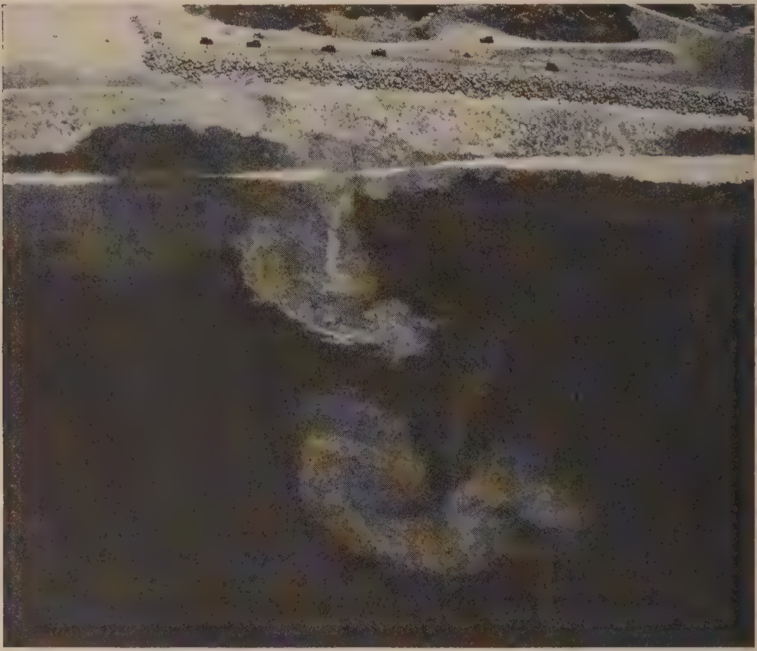

FIG. 7.—Showing the curling edges of an advancing rip current. Note that a new addition to the current is moving out from the shore. Official United States Navy photograph.

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[10] Shepard and La Fond, "Undertow," *Science*, Vol. LXXXIX (new ser., 1939), pp. 78–79.

evident at the surface, were also operating along the bottom in a depth of 5 feet of water. In another rip the outward movement along the bottom was found to be limited to a depth of 6 feet, although the outward movement at the surface continued more than twice as far from the shore to a point where the water was 16 feet deep. At another time current measurements were being made at the end of the Scripps pier in water about 18 feet deep, when a rip current was seen to move out over the spot where the measurements were in progress. Since the current meter near the bottom recorded continuous movement parallel to the coast while the current at the surface was moving seaward, it was evident that the rip had passed over the bottom water. Further indication that the currents do not reach great depth is derived from the fact that soundings show the absence of important channels along the bottom out beyond the neck of the rip current (Fig. 6).

The observation that floating objects are ordinarily carried out the neck of a rip current only to the point where the larger waves break, while the rip itself is seen to extend well beyond the breakers, indicates that there must be a greater transfer of water outward beneath the surface than at the surface. To test the nature of this subsurface current, large crossed vanes were suspended from a float to a depth of about 2 feet from the surface. A flag was placed on the float so that its motion would be observed. Since the movement would be more dependent on the pressure against the vanes than against the small float, the motion would be indicative of the subsurface current. The apparatus was put into a feeder channel of a rip current. After some lateral movements caused by oncoming breakers, it moved with a velocity of nearly 1 mile an hour out through the breaker zone and continued seaward beyond (Fig. 6). This movement was in contrast to that of kelp, which is often held up in the breakers as explained above.

On the other hand, it should not be supposed that this greater velocity just below the surface produces any appreciable tendency to draw a swimmer beneath the surface. Observations by the writers are supported by information from lifeguards showing that, while a swimmer's body may be tilted by the subsurface flow, there is little if any tendency to be pulled under the surface.

CHANNELS IN UNDERLYING SAND

The existence of channels in the sand along the path of a rip current has long been observed by lifeguards. Their presence was reported by all guards with whom the writers have talked. Surveys of these channels were initiated after a chance discovery of one several feet deep off the Scripps Institution. Several surveys of that channel were made and subsequently of other channels along a stretch of beach extending for $\frac{1}{3}$ of a mile south of the Scripps Institution.

Methods of survey.—Since the inner portion of a rip current is within the breaker belt, surveying of the bottom is very difficult. Some attempts were made to take soundings from a rowboat within the breaker belt, but this proved to be both difficult and dangerous, and the results were somewhat uncertain, particularly since it was found to be hard to concentrate on the work sufficiently to judge average wave levels.

A more successful method for the breaker zone consisted of wading and swimming out along prepared ranges on shore to cross ranges along the Scripps pier. The depth was determined by observing the water level on the surveyor's body. Help given the project by Dr. Roger Revelle was particularly valuable in this connection, since Dr. Revelle has a height of 6 feet, 4 inches.

Seaward of the principal breakers and to some extent within the belt, wire soundings were made from rowboats and depths determined with the usual sounding sheave. In the wading-swimming surveys, periods of low tide were chosen, while periods of high tide were picked for the boat surveys so as to have the least interference from breakers. The tide corrections were made after the surveys. Probably errors of as much as $\frac{1}{2}$ foot were due to the uncertainty as to mean level between the trough and crest of waves. Also, in studying the charts illustrating these gullies, it should be borne in mind that the outer portions were ordinarily not surveyed on the same day as the inner channels. Possible changes of depth may have intervened.

Relation to breaker zone.—The soundings and contours in Figures 6, 8, 9, and 10 will show the nature of the channels which are related to rip currents. Figure 8 indicates the possibility that the channel may continue out beyond the breakers. However, the sounding data were scarce outside, and there is no definite proof of the existence of the outer channel. Furthermore, in a more extensive survey shown in Figure 6, the outer portion, which was in an intensive rip

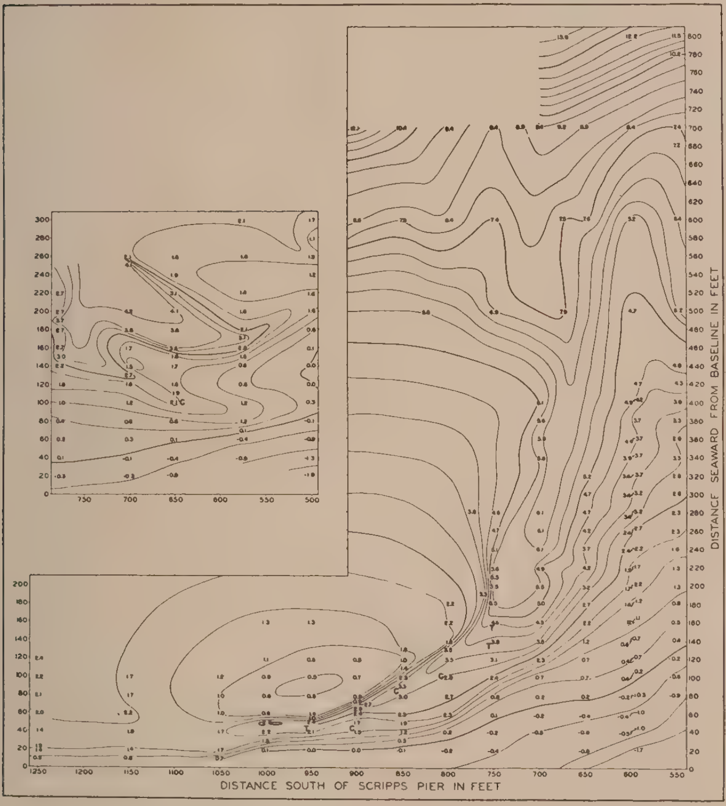
DISTANCE SOUTH OF SCRIPPS PIER IN FEET
DISTANCE SEAWARD FROM BASELINE IN FEET

FIG. 8.—A survey of one of the channels associated with a rip current. Note the curving feeder channel extending into the neck. The inset shows a resurvey of a portion of the same area made after an interval of 12 days. Note that in the inset the feeder channel enters from the north rather than from the south. In the main diagram the two sets of soundings along the range 600 feet from the pier were made on successive days, with those on the left made first. The symbol *T* indicates the presence of terrace material on the channel floor. The symbol *C* indicates the presence of loose cobbles. Soundings are reduced to mean lower low water.

head, had no clear indication of a channel. Therefore it seems likely that the channels are features largely confined to the breaker zone.

Character of the channels.—Some of the channels are developed only in the neck of the rip current, but most of them have one arm which is located on the side of the feeder current having the greater velocity. These feeder channels are found so near the shoreline at low tide that a child may step out from the beach and fall directly into water beyond its depth. In Figure 8 it will be seen that one of these channels ran parallel to the shore for 200 feet. Seaward of the channel the water was very shallow above a bar. The term "ball and low"[11] might be applied to the bar and adjacent channel. During the survey a very conspicuous current was moving along this channel toward the outer trough. Also there was a weaker current moving south along the shore on the other side, but no feeder channel appeared on that side.

In Figure 8 it will be seen that the steeper side of the inner channel is toward the breakers. It happens that this is the inside of the curve which is contrary to the usual steep side in a land gully. However, in another case (Fig. 9), the shoreward side of the channel proved to be the steeper, so that no rule can be established regarding this steepening.

The channel in Figure 9 is cut to a depth of about 3 feet below its surroundings with the deepest entrenchment near the point where the channel assumes an outward direction. It will be seen that beyond this point there is a gradual decrease of the depth of the channel below its surroundings.

The floor of most of the channels was found to be decidedly irregular, so that it was difficult to walk along them for this reason as well as because of the strong current. In some of the channels there was a series of disconnected basins (Fig. 9) having a depth of half a foot or more below their sills.

Hard bottom.—The bottom of the inner channels off the Scripps Institution was found to consist in part of the same Quaternary terrace alluvium that is found in the low cliffs inside the area investigated. Since the channel shown in Figure 8 headed off a gully in the land cliffs, it was thought possible that it might be following an old submerged stream course that had been re-excavated by the

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[11] D. W. Johnson, *Shore Processes and Shoreline Development* (New York: John Wiley & Sons, 1919), p. 486.

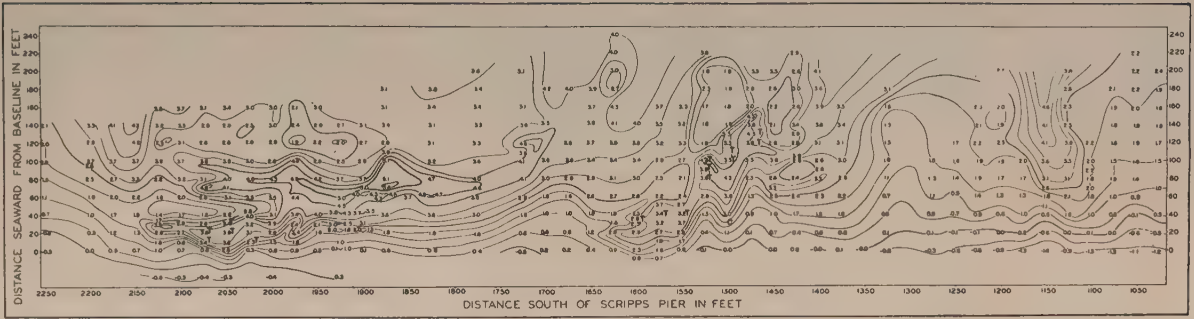
DISTANCE SEAWARD FROM BASELINE IN FEET
240
220
200
180
160
140
120
100
80
60
40
20
0
2250
2200
2150
2100
2050
2000
1950
1900
1850
1800
1750
1700
1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
DISTANCE SOUTH OF SCRIPPS PIER IN FEET

FIG. 9.—A survey of rip-current channels in an area to the south of that in Figure 8. The irregular bottom is thought to represent a stage in the fill of the channels. The symbol *T* indicates the presence of terrace material on the channel floor. The symbol *C* indicates the presence of loose cobbles. Soundings are reduced to mean lower low water.

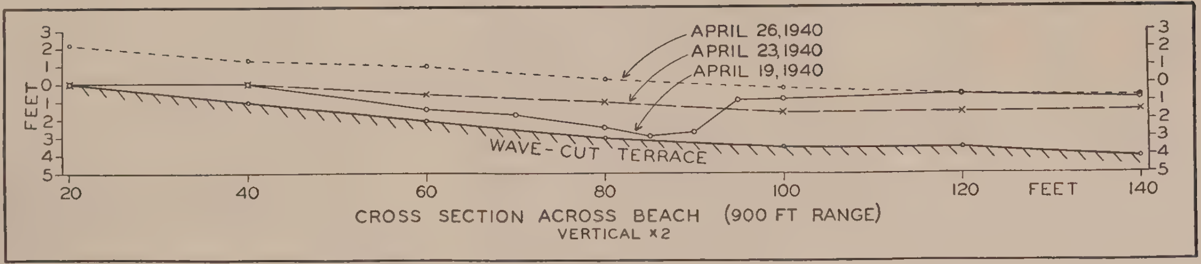

FIG. 10.—Cross section showing the relation of a feeder channel to the underlying wave-cut terrace on three occasions. Note that the channel became eliminated by April 26. Soundings are reduced to mean lower low water.

rip current. However, probing of the sand showed that the rip had not excavated below the level of the wave-cut terrace (Fig. 10) and that the relation of the channel to the land gully was only coincidental. The presence of fresh animal borings[12] in the terrace material of the channel bottom confirmed the absence of any excavation by the rip current into the underlying material.

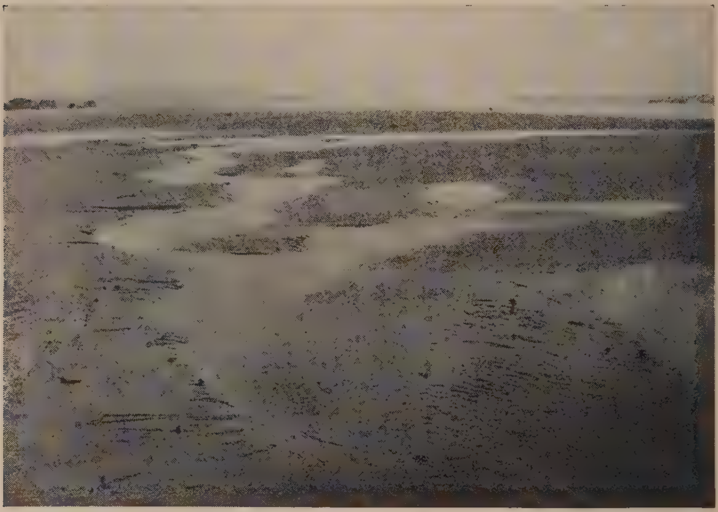

FIG. 11.—Showing the channels appearing at a very low tide on Mission Beach, where rip currents had been operating. Photo by Captain C. W. Hardy of the San Diego lifeguards.

Shifting of the channels.—There are some places where permanent rip currents are said to exist, and, therefore, more or less permanent channels can be expected. These rips are controlled by some artificial structure such as a pier, a groin, or in some cases the entry of a drain. At Scripps Institution the rip currents were found to vary in position considerably. Also successive surveys showed relatively rapid changes in the position of the accompanying channels.

The changes in such a channel are illustrated best in the cross sections of Figure 10. Another illustration of such a change is seen in Figure 8 in the inset showing a resurvey of a portion of the area of Figure 8. It will be seen that here the feeder channel is entering from the north, while in the main portion of Figure 8, based on a survey made 12 days earlier, it was entering from the south. It is notable that the main feeder current had also changed direction, showing the clear relationship between the currents and the channels. Three days after the survey of Figure 8 inset, the inner channel had completely disappeared and no appreciable rip could be observed in the locality.

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[12] The freshness of the borings is indicated by the presence of live *Exosphaeroma amplicauda* within the holes.

By repeating the surveys some idea of the history of development and of the changes in the channels was obtained. It seems likely that in the earlier stages of channel development the bottom is relatively smooth and slopes outward more or less continuously as in Figure 8. Later, when the currents are less pronounced, bars develop along the course of the channels, and the outward continuity is lost. This stage is illustrated in Figure 9. Small, somewhat circular holes in the beach are the only remnants of the channel at a later stage. These are sometimes exposed at low tide (Fig. 11).

RELATIONSHIP TO OTHER PHENOMENA

GENERAL

Daily records have been kept for several years at the Scripps Institution showing the character of the waves and the nature of the currents. During one year the height of the sand under the pier was measured daily at forty-five stations, and during five years it has been measured at periods varying from semi-weekly to weekly.[13] Also for many years the pier has been a tidal station of the Coast and Geodetic Survey, and other records, such as water temperature, wind velocity, and rainfall, have been recorded. In addition, since November, 1938, the height of the sand at various points south of the Scripps Institution pier has been measured at intervals varying from daily to weekly. During more than one year, rip-current intensity was evaluated daily along the beach south of the Institution. While the evaluation is probably none too exact, it seems likely that important relationships can be drawn between the values given to rip-current intensities and other conditions for which a numerical value can be given.

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[13] Shepard and La Fond, "Sand Movements along the Scripps Institution Pier," *Amer. Jour. Sci.*, Vol. CCXXXVIII (1940), pp. 272–85.

RELATION TO WAVES

Records at La Jolla.—Undoubted relation between intensity of rip currents and height of waves has been found from the records maintained at the Scripps Institution (Figs. 12 and 13). It was first shown by daily notations made for approximately a year in connection with the sand survey of the Scripps pier. These records, however, were made by various workers and are subject to a personal equation that makes them uncertain in value. A more systematic record was started by the writers in February, 1940, and is still in progress. The daily measurements of wave heights obtained on a wave machine[14] during this period are compared with the rip-current evaluation in Figure 13. It will be noted that the rip currents increase with every period of large waves, so that the largest values for rips correspond with the largest waves.

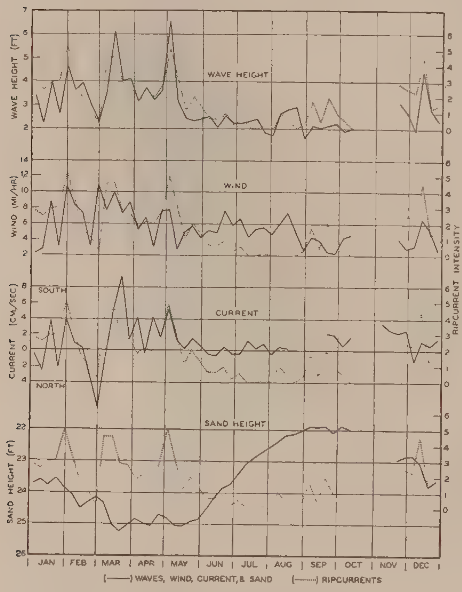

FIG. 12.—Showing the relation of rip-current intensity to wave height, longshore currents, wind, and sand height based on observations at the Scripps Institution during 1938. The data were obtained daily but are plotted as weekly averages.

Besides the height of waves, the period between crests and the smoothness of the wave records were examined to see if these characteristics had any bearing on rip-current development. It was found that in general small waves were more choppy or irregular in their form and had slightly longer periods between major crests than the large waves. As a result, the smooth waves because of their size would be accompanied by larger rip values. However, it is possible to determine whether the smoothness and the period of the waves were important in development of rips in the few cases where rip currents did not follow wave height with much fidelity. The result of this comparison showed that there is no pronounced relation between these wave characteristics and the rip evaluation.

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[14] *Ibid.*, Pl. I.

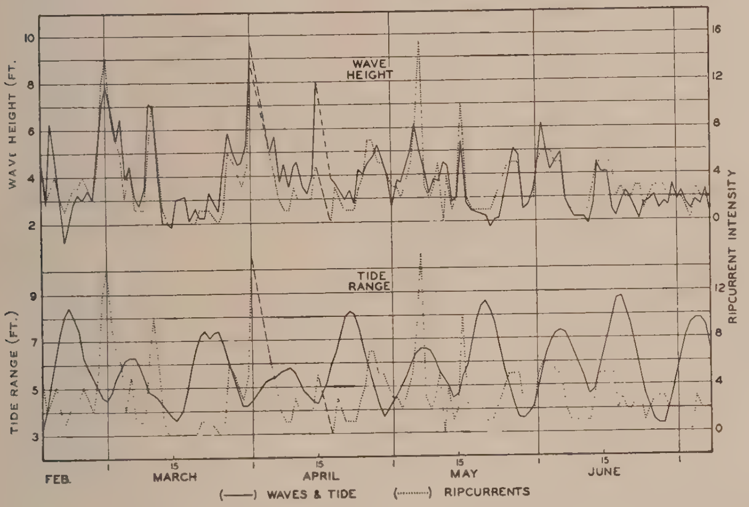

FIG. 13.—Showing the relation of rip-current intensity to wave height and tidal ranges at the Scripps Institution in 1940. These observations were made daily and are plotted as such. The high points on the tidal curve indicate spring tides and the low points neap tides.

Wave and rip variations along different coasts.—Along the coast south of the Scripps Institution (Fig. 1) there is a distinct variation in the size of the waves. In the vicinity of the Institution the waves are relatively large, but to the south inside the head of the La Jolla submarine canyon the waves are almost invariably smaller. Still farther south, despite the protection of La Jolla Point, the wave size increases. Rips are largest somewhat to the south of the Scripps Institution but are negligible inshore from the submarine canyon.

South of the canyon rip currents of large size have been observed during periods of particularly large waves. The same relationship between the smaller waves and absence of rips landward of a submarine canyon is shown in air photos of the shore at the head of Monterey Canyon.

Observations along the outer exposed coast south of Carmel, California, were made on the same day as observations along the somewhat protected but otherwise similar coast of Santa Monica Mountains. Along the former there were large breakers, but along the latter only small waves were rolling in. Off the mountainous coast with the large waves there were impressive rip currents, whereas no appreciable rips could be distinguished along the mountainous coast with small waves.

Similarly, along the east coast of the United States the rip-current phenomena appear to be uncommon in the calm embayments of the Maine coast.[15] However, there are reports of these features (called "sea pusses") along the unprotected shorelines of New Jersey.

Relation to wave fronts.—The typical form of a wave front coming in to the shore south of Scripps Institution is shown in Figure 1. It will be noted that the wave front is relatively straight and the coast is broadly indented. It has been found that the rip currents are ordinarily greatest at the middle of the indentation. The waves come in most directly onto the coast in this section, while they are somewhat diagonal to the shoreline on either side. A similar relation to indentations of smaller scale has been referred to above. Possibly also the usual absence of rip currents along the Santa Monica Mountain coast and their presence at Venice and Playa del Rey farther south may be due to the fact that the waves come in more diagonally along the Santa Monica Mountains than they do farther south.

RELATION TO CURRENTS

The relation of the rips to the currents measured at the end of the pier is shown in Figure 12. The weekly averages which are shown in the 1938 series of measurements decidedly indicate that the rip currents vary with the direction and intensity of the currents at the pier end. The periods of currents flowing to the south are in general those of strong rips, whereas the periods of northerly currents correspond with weak rips. This relationship is less impressive where the more exact rip-current data of 1940 are compared with the daily record of the currents at the pier end. However, even in this record, the change from north-flowing to south-flowing current shows in general an increase in the rip currents. In a number of instances the rips show a growth when a north current slackened, in spite of the fact that the waves had subsided from their peak. Examples of this relationship are to be seen on March 10 and May 7.

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[15] On the other hand, tide rips, which are actually due to the tide, are very pronounced along many of the narrow passages of the Maine coast. Rip currents also exist on the open coast. One was observed along a rocky promontory at Deer Isle, Maine, during a storm.

On the other hand, the relation of the current to the rips in both records is decidedly less constant than is the relation of the wave height to the rips. Thus we find large waves and large rip currents on April 26, despite a decided northward current. On May 12 the relationship of rips to current direction is also reversed from the normal, but in this case the relatively large waves had no rips associated with them, so that neither influence appears to have played a part.

An unfortunate feature of the current record prevents a completely satisfactory correlation with the rip-tide evaluations. The current meter at the end of the pier has to be taken out of the water during excessively large waves in order to preserve it from damage. Therefore, the nature of the currents on days when the rips are especially large is not well known. Future direct observations may remedy this condition.

RELATION TO WINDS

Indirectly the rip currents are related to winds, since winds produce most of the waves. However, along the coast of southern California, the large waves appear to come largely from storm centers at a considerable distance from the coast. Frequently large waves roll in accompanied by no appreciable wind. Also, the period of relatively strong winds at La Jolla extends somewhat longer into the late spring than does the period of large waves. The rip currents subside with the large waves, and strong rips do not occur on the windy days of late spring and early summer when the waves are small.

On the other hand, the rip currents may be distinctly related to the direction of the wind. Rip currents appear to be small when the wind is blowing along the coast. A good example of this was observed near San Simeon, California. To the north there was little wind blowing, and large rips were in operation; but to the south, where the land juts out at Point Piedras Blancas, the wind was blowing violently along the coast, and rip currents were inconspicuous. However, on one occasion, rip currents were observed at La Jolla when there was a strong longshore wind, but in this case heavy runoff due to a violent rain was piling up water along the shore and supplementing the effects of the breaking waves.

RELATION TO TIDES

Since the tides produce currents, it might be supposed that the rips would be stronger at spring tides, when these tidal currents are at their maximums. However, a plotting of the daily tidal range in the same curve with the rip-current evaluation shows that the rips have no evident relation to the spring and neap tides (Fig. 13). The cases where the wave-height and rip-current curves are at slight variation are not explicable on the basis of tides.

In one way, however, the tides may have some influence on rip currents. During low tide the water is sufficiently shallow to concentrate the flow of the current within the rip channels, whereas the deeper water at high tide is less confined by the channels. Observations at the Scripps Institution give the impression that rip currents are more pronounced at low tide. On the other hand, in a paper by C. P. L. Nicholls,[16] the statement is made that "it is usual for the rip tides to disappear at low tide, and it is likely that most rip tides will occur at high tide." Whether this inconsistency is due to a difference of locality of observation is uncertain.

RELATION TO CUT AND FILL OF BEACHES

The numerous measurements of sand height along the Scripps Institution pier[17] and along the beach to the south of the Institution afford another check on the various influences on rip currents. The times of year when the sand is cut low along the inner portion of the Scripps pier are also times when the rip currents are strong, while the times of high sand along the inner pier correspond with times of weak rips (Fig. 12). However, this correspondence may be explicable purely on the basis of wave size, since the large waves of winter produce cutting of the sand and the small waves of summer produce fills. Furthermore, large waves are accompanied by large rips, whether or not the beach is cut away. On the other hand, there is reason to believe that the locations of the principal rip currents near the Scripps Institution are associated with beach indentations and thus with sand level at these places. For several years it has been found that the beach is cut to its lowest level for the year off the Institution several months later than in a zone about 1,000 feet to the south. The rip currents also appear to be somewhat larger off the southern zone at an earlier date and off the Scripps Institution later.

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[16] "Rip Tides and How To Avoid Their Perils," *Calif. Beaches Assoc.*, Vol. I, No. 9 (1936), p. 12.

[17] Shepard and La Fond, "Sand Movements along the Scripps Institution Pier," *loc. cit.*

ORIGIN OF RIP CURRENTS

PREVIOUS SUGGESTIONS

In describing a phenomenon which he called "undertow" but which was clearly a rip current, M. P. Hite[18] referred to the piling-up of water along the shore behind a submerged bar and to the return of this water along channels. Nicholls[19] attributed rip tides to any features which "break up this littoral current resulting in variance in the ocean bottom." He also states: "Rip tides usually are caused . . . . by converging currents." These opinions are upheld by the present investigation.

INADEQUACY OF UNDERTOW

The common landward movement of floating objects[20] and the rapid movement in that direction in the breakers show that the surface water over most of the area is moving landward. This mo-

[18] "The 'Undertow,' " *Science,* Vol. LXII (new ser., 1925), pp. 31–33.

[19] *Op. cit.*, p. 12.

[20] T. Levi-Civita, "Über die Transportgeschwindigkeit einer stationaren Wellenbewegung," *Vorträge aus dem Gebiete der Hydro- und Aerodynamik* (Berlin, 1924), pp. 85–96.

tion may be compensated either by a return seaward in the form of undertow along the bottom or as a concentrated outward flow of surface and near-surface water as a rip current. The prevalence of rip currents shows that the return is largely by the second method. The reason for the dominance of the rip currents is that undertow is impeded by two factors. In the first place, there is more friction along the bottom so that outward flow is easier at the surface. Second, sea water is stratified to a certain extent with the heavier water underneath. As a result the light surface water cannot displace the water in this heavier zone. The effect of density stratification, however, cannot be important in the breaker zone where the water must be quite thoroughly mixed, but in the head of the rip beyond the breakers this factor may be very important. The frictional effect is evidently of considerable importance in the breaker zone, since near-shore observations along the Scripps pier have shown that objects in suspension near the bottom of a rip do not move outward nearly so fast as objects near the surface.

CHANNELS AS A CAUSE OF THE RIP CURRENTS

While there can be little doubt that groins and piers are an important cause of rip currents, as stated by Nicholls,[21] the relation of channels in the sand as a cause of these currents is not so clear. Rips have been observed in the absence of channels. Also the longshore channels or lows are found in the absence of rips. On the other hand, the channels associated with necks of the rip currents have not been observed as yet without currents.

Investigations of ball and low along the Scripps Institution pier have shown that these longshore channels and bars are developed principally as an accompaniment of longshore currents and may form under conditions of either small or large waves. During the development of the phenomenon the chief process appears to be the excavation of the low rather than the building-up of the ball. According to Lieutenant Warren,[22] such channels grow in length in the direction of the prevailing longshore currents until they make contact with a minor gap in the ball. This gap serves as a means for the water moving alongshore in the low to escape seaward, forming a rip current. Thus the low becomes also a feeder channel of a rip current. This rip current presumably deepens the initial gap and forms the outward-trending channel beneath the neck of the rip current. The more pronounced the channel, the more the rip tends to remain in this place.

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[21] *Loc. cit.*

[22] Personal communication.

It seems likely that the channels are caused primarily by the rip current, although an initial shallow indentation may localize the rip, as is shown by the channel on the right of Figure 9, which was not present a few days earlier in the survey shown on the left of Figure 8. The rapid filling of channels when conditions change, as above, shows the partial independence of rip currents from channel locations.

EFFECT OF CURRENTS AND WAVES

It has been shown that, in general, abundance of rip currents appears increased by southward-flowing currents as measured from the pier and decreased by northward-flowing currents. The cause of this relationship can perhaps be determined from an examination of the coastal configuration (Fig. 1). Relatively straight waves piling onto the broadly curved beach south of the pier should cause a northward transport at the south end of the beach and a southward transport at the north end. Such opposite movements tend to pile up water in the middle of the beach, producing rips. Thus times of southward currents at the pier should tend to correspond with periods of stronger rips in the middle of the beach.

Since the principal rips are found south of the pier, currents flowing to the south would feed these rip currents, whereas currents flowing to the north would tend to remove water from the rip area. Furthermore, a general longshore current flowing to the north does not meet with any obstruction which might lead toward the piling-up of water. The relative straightness of the coast continues for almost 100 miles in that direction. On the other hand, $1\frac{1}{2}$ miles to the south the coast bends outward to form La Jolla Point, which may cause a piling-up of the water during times of south-flowing currents. This excess water may escape partly in the form of rip currents.

When once an outward-flowing current is initiated, it tends to weaken the breakers locally. The smaller the breakers along the path of the rip current, the faster it can flow. Thus the rip current accelerates until the head of water onshore, which was due to the piling-up effect of the two opposing currents, has been sufficiently lowered so that the rip dies down awaiting the buildup of another head. This sequence accounts at least in part for the spasmodic flow of the rips (Fig. 7).

While the local longshore currents play an important part in the development of rip currents, the close relationship shown between the rip evaluations and the size of waves shows that the waves must be the dominant factor. The larger the waves, the more water is piled onto the shore, and, therefore, the more water has to return seaward. However, the height and trend of the waves are largely responsible for the development of the local longshore currents, so that these two factors are interrelated.

SIGNIFICANCE OF RIP CURRENTS

EFFECT ON BEACHES

Rip currents have both a direct and an indirect effect on beaches. Their direct effect is the production of channels and holes in the portion of the beach exposed at lowest tides. The indirect effect comes from the presence of indentations inshore from the channels which allow the waves to wash higher on the shore so that they may have more erosive action inside the rip current.

OUTWARD TRANSPORTATION OF SEDIMENT

Sorting of beach sands.—It has been generally assumed that beach sands become sorted by the breaking waves stirring the sand and the backwash carrying the fine material into the undertow current, which in turn carries the load seaward.[23] If undertow is eliminated as an important process, rip currents are still available as a means of carrying the fine sediments well beyond the beaches. In this process the wave-stirred sediment is carried along the feeders to the neck and thence beyond the effect of breaking waves.

As an example of the operation of this process observations made near the Scripps Institution may be cited. After the great southern

[23] See, e.g., C. R. Longwell, A. Knopf, and R. F. Flint, *Textbook of Geology* (2d ed.; New York: John Wiley & Sons, 1939), p. 200.

California flood of March, 1938, the beach beneath low cliffs south of the Institution was covered with a thin mantle of mud. After one or two high tides this material was largely removed from the beach. Much of it could be seen moving seaward in the large rip currents which were in operation. Samples taken along the Scripps pier showed that the mud had not lodged within a thousand feet of the shore. Similarly, after winter floods had carried large masses of muddy sediments down the slopes of the Santa Lucia Mountains onto the beaches, large rip currents were observed carrying the fine sediment seaward.

A source of offshore sediment.—The evidence given above indicates that rip currents carry fine material seaward, but their limited outward extent might be supposed to restrict them to near-shore zones as a transporting agent of sediment. Off southern California the chief sites of sedimentation are thought to be the offshore basins and troughs.[24] However, since the chief source of sediments for these basins must be the land, any process which can carry fine sediment out from the shore must be important. Furthermore, it should be remembered that there are other types of currents out beyond the zone where rip currents predominate, and the suspended sediment carried out by the rips must be transferred to a considerable extent into the offshore currents in which it may be carried to the various basins before settling-out of suspension.

An example of this ferrying of sediment from shore out into the main circulation was observed from the "E. W. Scripps" while anchored off the mouth of the San Dieguito River following the March, 1938, flood. Muddy-water zones were seen to move out from the shore in a series of pulsations with marked color boundaries at the front of each advancing mass. These outward-moving masses of muddy water closely simulated typical rip currents except that they had much more suspended sediment. However, the outward movement was presumably due to the piling-up of water by the entering river rather than by the waves; but, whatever the cause, these outward-moving masses were supplying the offshore currents with large quantities of suspended mud.

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[24] Roger Revelle and F. P. Shepard, "Sediments off the California Coast," *Recent Marine Sediments* (Tulsa: Amer. Assoc. Pet. Geol., 1939), pp. 245–82.

POSSIBLE RELATION TO SUBMARINE CANYONS

As yet no one has attempted to show that rip currents are the cause of submarine canyons. However, this oversight may be due to lack of information concerning these currents. The concentrated outward flow of the rips on open coasts gives them a distinct advantage as a canyon cause over other known types of oceanic currents. Also, their associated gullies may serve to stimulate interest concerning possible relation between the rips and submarine canyons. Furthermore, the absence of large breakers at the heads of canyons and their presence on either side suggest the possibility that water piled up by the breakers might return seaward along the axes of the canyon. There is some evidence that currents do move toward the canyon heads.[25] Also the evidence accumulated in work on the "E. W. Scripps" has shown that where canyon heads approach the California coast little sedimentation has taken place on the canyon floors.

On the other hand, the importance of rip currents either as a cause of canyons or even as a means of keeping them clear of sediments appears unlikely for the following reasons:

1. The observations given above suggest that the currents do not extend more than a few feet below the surface.
2. The density stratification of ocean water must act as a serious impediment to deep circulation of such a current.
3. The rip currents are not known to extend outward more than about ½ mile, which is in great contrast to the submarine canyons which extend out for as much as 100 miles.
4. After the occurrence of large waves, with their accompanying large rips, examination of canyon heads has failed to show evidence of deepening.
5. Evidence given above shows that rip currents in the vicinity of La Jolla are much less pronounced around the head of La Jolla Canyon than they are on either side. Airplane photographs of the coast at the head of Monterey Canyon also show that there are rips on either side and an absence of rips at the canyon head.
6. The scoured condition of the canyon heads can be explained by the mud flows and other types of submarine slipping which are known to occur at these places.

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[25] F. P. Shepard and K. O. Emery, "Submarine Topography off the California Coast: Canyons and Tectonic Interpretations," *Geol. Soc. Amer., Special Paper No. 31* (1941), p. 103.

Accordingly, the present state of our information gives little ground for connecting the submarine canyons with rip-current movements. Whether these currents may play some slight part in canyon development or in clearing out the canyon heads during unusually large wave periods remains to be seen.

A MENACE TO SWIMMERS

Lifeguards who have been consulted by the writers are of the opinion that rip currents are the dominant cause of trouble encountered by bathers. There appear to be two principal locations where swimmers get into difficulties. The first and most common location of rescues is in the rip-current neck (Fig. 5), at the point where the large waves are breaking. A bather may find himself in this position either by slipping into a feeder channel, which may be very near the shore, and being swept out into the neck or by jumping through breakers in the zone next to the rip-current neck and being pulled gradually toward the neck until, having reached the main channel, he finds that he is in water beyond his depth. Ordinarily a person getting into the neck will not be carried beyond the breakers, but the outward-moving current may prevent all but a very good swimmer from progressing landward. As a result, the victim finds he is being buffeted by each oncoming wave but is making no progress toward the shore. Furthermore, if he has slipped into the neck from shallow water along the side of the channel, his attempts to swim parallel to the coast back to shoal water may not succeed because the water may be moving toward the neck with considerable speed from that side (Fig. 5). The solution for a swimmer caught in this situation is to try to swim out of the rip to the side opposite that from which he entered the neck (Fig. 5). If he does not get out on one side, he should try the other. Probably there are times when this method would not succeed, since water may come in forcibly from both sides. In this case a good swimmer can go out through the breakers and escape as explained below.

The second situation of danger is beyond the breakers. A swimmer may have gone through the breakers in a rip current or may have swum into a rip while swimming along the coast outside of the breakers. Turning toward shore, he may find that he can make no progress. The current in the head is not ordinarily very strong, but most swimmers are not very fast. In some cases the rip is of short duration so that only a little patience is necessary; but at other times the rip, even if somewhat pulsatory, continues to move outward over a long period of time. The solution for a bather caught in this situation can be seen from Figure 5. He should swim parallel to the shore and, after a relatively short distance, will be helped by the laterally moving current of the rip. Then, after getting out of the turbulent rip, in coming landward he will be further assisted by the shoreward-moving surface water next to the rip. Two possible difficulties may be encountered in attempting this procedure. Sometimes new rips develop adjacent to old ones, so that the swimmer might have to go a considerable distance parallel to shore before escaping. Another trouble may be that the swimmer having reached shallow water successfully may stumble into the feeder channel and be swept out into the neck of the rip in a fatigued condition. This last difficulty can be avoided by approaching the shore with caution and going around any feeder channel.

The dangers of rip currents are such that swimmers should exercise considerable precaution in their surf swimming. Careful scrutiny of the breakers will usually show whether there are dangerous rips present. Also the swimmer will do well to go out from broad projecting points rather than from beach re-entries where rips are most common. Particularly should he avoid piers and groins or other engineering structures which might deflect outward a longshore current. Since the danger exists only when the waves are large, bathing in summer is ordinarily free from such difficulties even on open coasts.

SUMMARY AND CONCLUSIONS

Along coasts where large breakers move landward over a shallow-water platform the cumulative landward movement of the surface water is compensated by seaward-moving lanes of water which extend out normal to the beach. These water masses, moving contrary in direction to the wave approach, are given the name "rip currents." According to available evidence they appear to take the place erroneously assigned to undertow, in that they return the water which tends to be piled onto the beach by the waves and in doing this carry seaward fine sediment derived from the land.

Rip currents are ordinarily fed by water moving along the shore from either side. The two currents join and extend out in what is known as the neck, where the water rushes through the breakers in a narrow lane. Beyond the breakers the current spreads out in what is called the "head" and dissipates. The outward-moving columns can be recognized by their brownish color if they contain abundant sediment, by their agitated water, or by an extension of foam belts well outside the line of breakers.

These currents are ordinarily long and narrow, but in their outer zone they widen considerably. They extend out from a few hundred up to about 2,500 feet from the shore and vary from narrow belts 50 or 100 feet across in the feeders and neck to as much as 500 feet or more in the heads. Their velocity is known to be as great as 2 miles an hour in some instances. This rate of flow is very inconstant, being greatly checked or even stopped by advancing wave fronts. The flow is capable of erosion near the shore where it produces channels a few feet deep. These channels may change in location and in form in periods of a day or even during the change of a tide.

Rip currents are important as a means of transporting fine material from the shallow water along the shore into the main-current circulation outside a coast. They are also a considerable source of danger to bathers, since their velocity is such that a swimmer may not be able to make progress against them. Most rescues from the surf along the coast of southern California are made in these rip currents.

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TRANSPORTATION OF ROCK BY KELP*

BY K. O. EMERY AND R. H. TSCHUDY

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ABSTRACT

In addition to being rafted by ice and by drifting logs, pebbles may be carried by kelp holdfasts to be dropped into deep-water sediments after the floating kelp has decayed or been eaten. Many shallow-water organisms similarly may be deposited in foreign environments. Numerous pebbles and cobbles still attached to kelp have been picked up on beaches, and in at least two instances pebbles with remnants of holdfasts have been found in relatively deep dredgings of the ocean floor. Although large kelps with floats are limited essentially to the Pacific and Antarctic regions, smaller algae from other coasts are also known to raft pebbles and shells long distances.

INTRODUCTION

In the past, geologists have occasionally noted the sporadic presence of pebbles and cobbles in fine-grained sedimentary rocks. Since water cur-

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rents which carry fine debris in suspension usually can not transport pebbles, some other agency is required to account for their occurrence in relatively well sorted sediments. In some instances the presence of these pebbles has been explained by their being rafted on icebergs or floes (Savage and Griffin, 1928; Reynolds, 1928; Bradley, 1940) and in others by their being carried in the roots of drifting logs (Spencer, 1887; Dana, 1895). More rarely suggested is transport by kelp holdfasts (Kinahan, 1879; Ball, 1888; Shaler, 1894; Ellis and Lee, 1919). This method of rafting is difficult to recognize in ancient sediments because the holdfasts are readily decomposed. However, examination of rocks gathered on beaches or recovered by dredging the sea floor throws more light on this means of transportation, since the rocks may be collected before the holdfast has been decomposed or eaten by organisms.

NATURE OF KELP

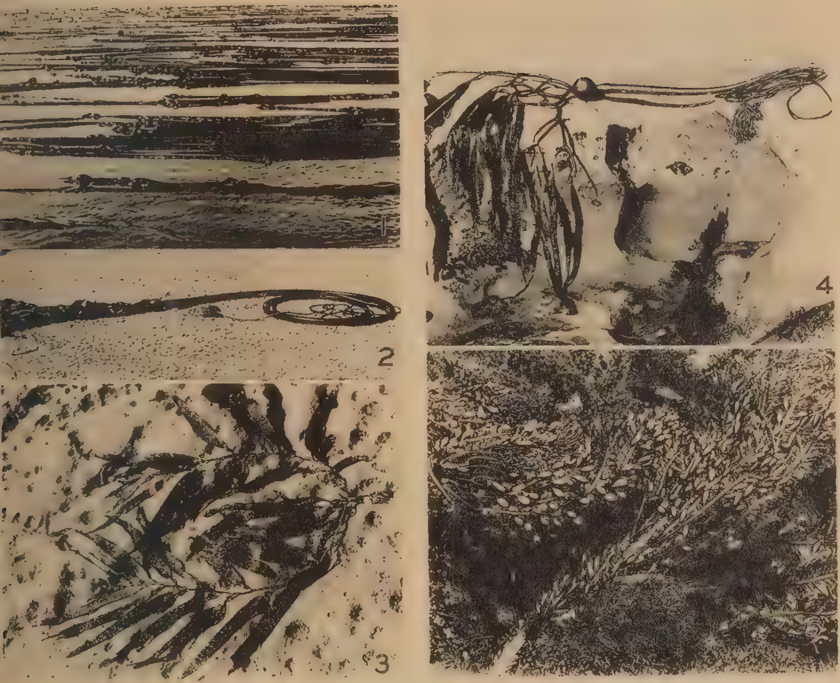
DESCRIPTION

General.—The term kelp has been used by some workers to designate the larger seaweeds. More recently, it has come to be used solely in reference to larger genera of the Laminariales, a family of the brown algae. With few exceptions, the larger seaweeds fall into this category.

Morphology.—The plant consists of two main parts—a holdfast, or rootlike structure, to anchor it to the bottom and an expanded photosynthetic portion called the blade. In some kelps the section between the holdfast and the blade, or lamina, is elongated and forms a long ropelike connection, the stipe.

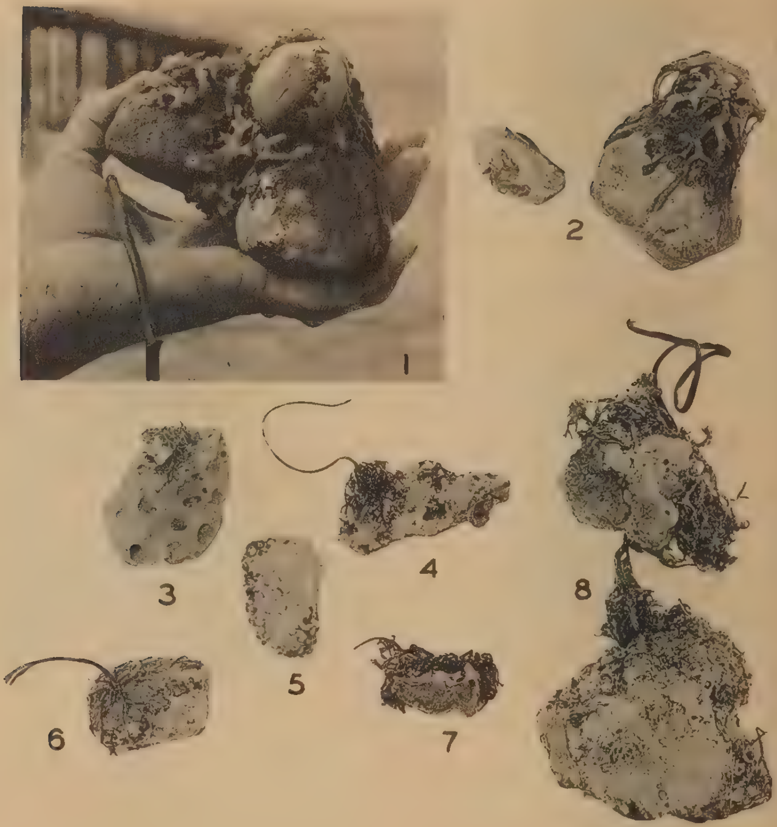
The holdfasts of different genera vary considerably but usually they are made up of dichotomously branching structures which form a hemispherical mass anchoring the algae to the bottom. In growth, when the tips of these branches come in contact with a solid substratum, they spread out slightly and fasten themselves firmly to it. Usually the holdfasts do not exceed 12 inches in diameter, but in *Macrocystis* they have been known to reach a diameter of 3 feet.

Algal floats.—Some species of marine algae have distinct floats which hold the photosynthetic tissue close to the surface of the water. *Nereocystis* and *Pelagophycus* are the most spectacular representatives of this group (Pl. 1, figs. 1, 2, 4). The cavity of *Pelagophycus* floats from the kelp beds near La Jolla have a volume of about 120 cubic inches. Larger volumes are reported for floats of *Nereocystis* (Zeller and Neikirk, 1915). *Macrocystis* and *Egregia* have much smaller but very numerous floats (Pl. 1, figs. 3, 5). A single *Macrocystis* holdfast may have attached to it a dozen or more stipes, each of which possesses a float at intervals of about



LARGER FLOAT–BEARING GENERA OF BROWN ALGAE

(1) Kelp bed made up of *Nereocystis* plants. (x$\frac{1}{65}$).
(2) Individual *Nereocystis* plant. (x$\frac{1}{65}$).
(3) Young *Macrocystis* plant.
Showing arrangement of fronds and new branches arising from base. (x$\frac{1}{25}$).
(4) An individual *Pelagophycus* plant. (x$\frac{1}{60}$).
(5) *Egregia* exposed at extreme low tide. (x$\frac{1}{12}$).



ROCKS TRANSPORTED BY KELP

(1) Two small cobbles of sandstone and one of metavolcanic attached to a young *Macrocystis* holdfast. (x⅓).

(2) Kelp-rafted pebbles of cherty limestone.
Found in dredgings made at a depth of 720 feet. Each holdfast is *Egregia*. (x½).

(3) Shale; worm and pholad borings; *Macrocystis* holdfast. (x¼).

(4) Shale; worm and pholad borings; encrusting algae, Bryozoa, and so forth; *Pelagophycus* holdfast. (x¼).

(5) Granodiorite heavily encrusted by calcareous algae; *Macrocystis* holdfast. (x¼).

(6) Metavolcanic; calcareous algae, young *Macrocystis* holdfast. (x¼).

(7) Sandstone freshly broken from a larger mass; calcareous red algae on former exposed surface. (x¼).

(8) Two angular rock fragments weighing 4.5 pounds attached to a single *Pelagophycus* holdfast. (x¼).

inches along its entire length. The buoyancy of an entire *Macrocystis* ant is, therefore, great, even though each float has a volume of not more an half a cubic inch.

Size.—*Macrocystis* is the largest of the marine algae, commonly reach- g a length of 200 feet and, exceptionally, as much as 600 feet. Adult ants of *Pelagophycus* and *Nereocystis* often are as much as 100 feet long, hile *Egregia* and *Alaria,* the only other marine algae of comparable size, e usually not longer than about 60 feet.

The weight of a single *Macrocystis* plant has been known to be as much 300 pounds, while other species commonly weigh not more than about 5 pounds (Frye, Rigg, Crandall, 1915).

Other much smaller species belonging to the family Laminariales play definite though probably a relatively minor role in the transport of ebbles.

Distribution.—The kelps find their best development in the North acific Ocean and in northern European waters (Setchell, 1893). They e present along the west coast of North America from Alaska to south of exico and along the east coast of Asia, in the Okhotsk Sea, and off apan. Skipping the equatorial region, they are again found along the est coast of South America, around the Antarctic continent, near Austra- a, and to a limited extent along the west coast of Africa.

The depth at which various algae are found depends upon several factors. he amount of light, turbidity of the water, and nature of the bottom are f importance. The brown algae are very seldom found growing in water s deep as 100 feet. The large kelps, such as *Macrocystis, Pelagophycus,* nd *Nereocystis,* commonly occur in water from 20 to 60 feet deep. *Egregia* sually lives in somewhat shallower water. Many of the smaller genera of arine algae, such as *Eisenia, Lessoniopsis, Laminaria,* and *Pterygophora,* ccur exclusively in the tidal zone or just below mean low water.

Geological history.—Although some kinds of algae are known from pre- ambrian rocks, the earliest occurrences of supposed brown algae, insofar s the writers are aware, are those reported from the Devonian and ilurian. Species of *Nematophyton* reported by Lang (1926) show the lamentous internal structure of the stem believed by some to indicate a elationship to the Laminariales. More recently, Krausel and Weyland 1930) have discovered in rocks of these ages indefinite algae-like frond npressions connected with stems of the *Nematophyton* type.

An occurrence of two fossil brown algae from Miocene diatomite de- osits has been reported by Gardner (1923). These algae appear remark- bly similar to species living at the present time.

RESTRICTION TO ROCKY BOTTOM

Because of the pull exerted by strong currents, kelp must be securely anchored to the bottom. Good anchorage can be found only in places where hard ledge rock or large boulders are present. Reports on the extent of kelp beds along the west coast of the United States and Mexico show that they occur chiefly in rocky areas and practically never on sandy bottom, unless the sand constitutes only a shifting veneer over the rocks (Crandall, 1915; Brandt, 1923). Similarly, examination of United States Coast and Geodetic Survey charts shows notations of rocky bottom in areas of major kelp beds.

DESTRUCTION OF KELP BEDS BY LARGE WAVES

High waves developed by storms have been known to reduce kelp beds to about half their former size in a relatively short time. This depletion occurs both by the breaking up of the plants and by their dragging anchor. The holdfasts may be torn loose from the substratum, or the rock anchor itself may be lifted up or pulled apart. If one plant is broken loose and drifts against its neighbor, the combined pull of both may cause the second plant to break loose. Such a drive may tear a wide swath through a kelp bed, having been known to involve as many as 30 plants (Brandt, 1923).

KELP HOLDFASTS WASHED ON BEACHES

DEEPER WATER KELPS

From 1937 to 1940, holdfasts were occasionally picked up on the beach at the Scripps Institution of Oceanography at La Jolla, California. Although no systematic gathering was attempted, about 100 holdfasts were found largely by Dr. F. P. Shepard. These evidently were carried from a large kelp bed about a mile off shore across a submarine canyon more than 300 feet deep.

On June 5, 1940, moderately large waves carried a somewhat greater than usual number of kelps to beaches inshore from the same kelp bed. Distributed along about a third of a mile of the beach north of La Jolla, 46 *Macrocystis* and *Pelagophycus* holdfasts were found (Pl. 2), of which 17 had rock fragments attached. Along about half a mile of Pacific Beach, south of La Jolla, there were found 47 more holdfasts, 7 of which carried pebbles. Allowing for the kelp washed ashore on portions of the beaches not searched, it is probable that more than 100 holdfasts with pebbles attached were washed ashore after only one day of relatively large waves. Although it is impossible to determine the number of kelps washed out to sea, the finding of this number carried a le or more to the beach indicates the effectiveness of kelp in transport- ; pebbles. A great deal of kelp may be carried seaward from the main- d by storms with offshore winds and probably it is washed seaward ntinuously from kelp beds surrounding islands.

ALGAE FROM SHALLOWER WATER

In several instances, *Egregia* (Pl. 1, fig. 5), which lives in relatively allow water near shore, has proven to be an important agent of rock nsport. A cobble beach, south of La Jolla, was found to be abundantly vered by rocks which still had a portion of the algae attached. In an a of about 1200 square feet 110 cobbles were collected, of which 16 re attached to *Egregia* holdfasts, two to *Dictyota*, and one to *Neuro-* *rpus*. Forty-six bore remnants of holdfasts which were too worn to mit identification of the type of alga. Forty-five other cobbles and bbles were covered by encrusting organisms similar to those on the bbles to which holdfasts were still attached. Since similarly transported ks were nearly evenly distributed over the entire cobble beach, which about 600 feet long and 75 feet wide, addition of rocks to the beach by lp rafting over a long period of time must be substantial. That this ndition is not unusual is supported by the collection of 207 holdfasts, iefly of *Egregia*, on a cobble beach at Devil's Slide near La Jolla. venty-two had rock fragments attached, mostly of Chico, Cretaceous ale.

Although less significant than large kelps whose floats enable them to carried a great distance, algae such as *Fucus, Dictyota, Neurocarpus, senia, Lessoniopsis,* and *Pterygophora* cause the transport of pebbles a ort distance toward shore from relatively shallow water (Johnson, 19; Andree, 1920). Most of these algae possess no floats but are often n loose from their anchorage by large waves at low tides and are car- d to the beach. The force of the waves may be so great that the rocks which the algae are attached may be transported to the beach along th the plant. After a period of large waves more than 100 plants of *erygophora* bearing rocks of various sizes were picked up along a few ndred feet of sandy beach at Point Conception, California.

That rafting by these shallow-water algae is not restricted to short stances is shown by Collins (1914), who reports finding pebbles and ells in the holdfasts of *Laminaria, Fucus, Desmarestia, Ascophyllum,* d *Rhodymenia* which had floated 150 miles from their point of origin.

CHARACTER OF ATTACHED PEBBLES

About two-thirds of the rock fragments picked up on beaches inshore om the La Jolla kelp beds consist of shale or sandstone probably of

Chico, Cretaceous and Rose Canyon, Eocene age. Most of the other specimens are rounded cobbles of Black Mountain meta-volcanics which occur in Eocene conglomerates. Some chlorite schists of unknown derivation were also found. All the rocks are partially encrusted by calcium carbonate depositing organisms such as Bryozoa, Mollusca, serpulid worms, and calcareous red algae (Pl. 2). Worms and pholads have made deep borings in the softer rocks.

The largest rock obtained is about 15 inches long, and the heaviest weighs about 13 pounds. Most of the holdfasts are quite large, though the pebbles attached are small. In one instance, more than 25,000 pebbles and granules larger than one millimeter in diameter were held by one holdfast. This suggests that a holdfast may be wrenched loose from a solid substratum but may retain its grasp on small loose pebbles which had lain on the surface of a larger rock mass.

TRANSPORT OF ORGANISMS

Many holdfasts picked up on beaches or found drifting in the water have shells attached to them. Fragments of pelecypod and gastropod shells are occasionally found, together with the more common serpulid worm tubes. Living organisms include starfish, brittle stars, echinoids, sponges, and many types of worms (Andrews, 1938). Encrusting organisms such as Bryozoa, Foraminifera, worm tubes, calcareous red algae, and others are attached to rocks of the holdfast (Pl. 2). Similar instances of transport of organisms by algae have been noted by Vallentin (1895). All these organisms are carried from their normal environment and are dropped by the floating kelp in areas where they would not normally live, perhaps to be incorporated in beach sands or in sediments of the deep sea.

HOLDFASTS ENCOUNTERED IN DEEP-WATER DREDGINGS

During 1938, many rock dredgings of the ocean floor off southern California were made from the research vessel E. W. Scripps. Samples at two localities include pebbles having an attached kelp holdfast.

At the head of Pedro Trough (a submarine canyon about 5 miles south of the Palos Verdes Hills) one dredging recovered an angular pebble 2 inches long, to which part of a holdfast was still fastened (Pl. 2, fig. 2). The rock is cherty limestone, possibly of Miocene age. Another dredging, taken half a mile away, also contained a holdfast and an attached pebble. This rock is smaller than that of the first dredging but is of similar lithology. Both holdfasts were found to be of *Egregia*. These dredgings were made at a depth of 720 feet, far below the depth of kelp growth. In each instance, the kelp probably floated seaward from the extensive beds surrounding the Palos Verdes Hills.

One questionable kelp-rafted pebble was found in another sample from e ocean floor. A core, taken in clean sand at a depth of 180 feet in a bmarine canyon off La Jolla, contained a rounded pebble of Black ountain metavolcanic rock similar to those frequently found attached holdfasts picked up on the beach near-by. This pebble has what apears to be a holdfast, but so little remains that it cannot be positively entified as such. Farther from shore in the same canyon a dredging at 20 feet recovered a holdfast, but no rock was attached.

SIGNIFICANCE OF KELP TRANSPORT

Since kelp holdfasts containing pebbles have been found frequently on arine beaches and also are known from dredgings of the sea floor, this ethod of transport should receive more attention than has been accorded . Such an agency may explain the occasional finding of erratic pebbles otherwise uniform fine-grained sediments. The presence of borings d of encrusting organisms on such erratic pebbles may serve to rengthen the possibility of kelp rafting. However, it is likely that ost of the rocks carried by kelp are deposited on beaches and are reorked into the beach conglomerate. Abrasion through the action of each processes quickly removes all traces of surface encrustations, makg the identification of kelp-rafted pebbles in ancient conglomerates ifficult or impossible. However, pebbles of unique lithology, angularity, size with respect to others in a conglomerate may have been carried y kelp to the beach.

Although only two certain cases of kelp-rafted pebbles have been noted dredgings off California, it must be remembered that dredgings and ores have recovered rocks from only an infinitely small proportion of e total area of the ocean floor.

During cruises of the research schooner, E. W. SCRIPPS, floating kelp as been noted as far as 250 miles from the nearest land (Roger Revelle, ersonal communication). Pebbles could easily have been carried by this oating kelp and have been dropped when enough of the floats had ecayed or been eaten by organisms.

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SCRIPPS INSTITUTION OF OCEANOGRAPHY, LA JOLLA, CALIF.

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Contribution No. 128

Reprinted from CHRONICA BOTANICA
Vol. VI, 16, pp. 365-367, May 5, 1941

W. E. ALLEN: **Frustules of Marine ankton Diatoms***:- For more than fifty ears interest has been steadily increasing the occurrence, distribution, and general lationships of marine plankton diatoms. riginally, this interest was based primar- / on the idea that these microscopic plants ere an important source of food for fishes for animals fed upon by fishes. Natural- this led to interest in the abundance of atoms as an indication of fertility in articular localities or regions. Near the ıme time it came to be realized that large opulations of these organisms profoundly fected the oxygen concentration and many her chemical conditions in their immedi- e vicinity, and that even thin populations ight exert chemical and physical influences ır from negligible in relation to a number details of characteristics of sea water. ater, improved methods of operation made possible to use diatom populations as upplementary indicators of mass move- ents of water in the sea and of changes chemical and physical details too deli- ate for direct observation. For a long me, petroleum geologists have been using eposits of diatom frustules (the siliceous ox-like coverings) as markers for certain eological horizons in many "oil fields". Iore recently geologists suspect that di- toms have been important contributors to etroleum accumulations.

Apparently, marine biologists, fisheries vestigators, marine chemists, marine hy- rologists, marine hydrographers, and even etroleum geologists are all interested fun- amentally in the living, active plant, and e conditions responsible for or resulting rom the changes in its populations. trangely enough, the diatomist whose in- erest in individual specimens might be upposed to center in their lives usually onfines his attention to the frustules. Fas- inated by beauty or variety of design in eir sculptures, by their differences in elicacy of structure, and by the surprising eculiarities of many of their forms he ives little heed to the living material pro- ucing them. As a matter of fact, it is not robable that the diatomist could give much elp to these other groups of observers if e did become familiar with living speci- ens of a few of his choicest species. Mass elationships would still have to be worked ut under field conditions.

An outstanding result of the influences of he natural impediments to observation, of he difficulties of investigation, and of the pecialization of interests has been to cause ll of the groups aforementioned to give heir attention primarily to the skeletal tructures (frustules) of diatoms rather han to other morphological characteristics r to functional relationships of individual pecimens. Thus one finds in diatom lit- rature a remarkable preponderance of description of the siliceous coverings and a still more remarkable treatment of the frustules of these plants as representative of the organisms themselves. Almost, one might conclude that the frustule is the thing. Evidently, there is no escape from the fact that diatom frustules hold a conspicuous place of their own in many problems of the sea.

As might be expected from their prominence, a considerable body of knowledge embracing a wide variety of facts, inferences, and speculations has been developed concerning frustules. If properly organized this would require an enormous amount of space for proper presentation. On the other hand, some of it may have appreciable value even under incomplete and somewhat superficial treatment. Following are some of the points appearing to me as especially interesting and suggestive after a long period of direct acquaintance with populations of marine plankton diatoms.

In the first place, there seems to be some reason for thinking that the frustule is an integral part of every vegetative diatom cell. Apparently there is no record of vegetative activity of a diatom protoplast devoid of its natural siliceous accompaniment. Furthermore, complete covering is rapidly restored when a part of the protoplast has been bared temporarily in the process of cell division. Also, it is claimed by some observers that diatoms do not thrive or survive for long when silica is absent or markedly deficient in the surrounding water. Nor is it difficult to imagine definite physical, chemical, and biological causes for or conditions of integral relationship. The fact that cells of a particular species normally take a characteristic rigid form suggests that that form is an expression of the hereditary trends in vegetative activity, of which the frustule is another expression. To the extent that the formation of the frustule entails an appropriate series of physiological changes in the growing cell and to the extent that it serves as a container which keeps all parts of the protoplast in their correct position it exerts physically an integral influence.

Concerning the chemical aspect, it may suffice to say that one cannot imagine that a protoplast suddenly deprived of its siliceous coat would or could proceed with the chemical changes incident to its vegetative routine without modification. Biologically, the frustule represents a certain amount of energy diverted to its construction and maintenance and its rigidity must play a considerable part in the distribution of work in life processes of the protoplast. Still more evidently, details of form and of sculpturing must play a prominent part in determining the energy requirements of operation, compact form and coarse sculpturing possibly permitting better results of vegetative activity than a rangy form with fine sculpturing. Perhaps most evident is the certainty that details of external form and of sculpturing must have notable influences on rates of sinking or on prospects of suspension at particular levels.

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*Contributions from the Scripps Institution of)ceanography, N. S., No. 128.

In the course of more than twenty years of investigations of marine plankton diatoms, and as a result of microscopic examination of diatom remains in about 25,000 catches (of which about 4,000 have been below the surface of the sea), the Scripps Institution of Oceanography has obtained much evidence to show that the surface level is as likely as any to be most productive at any particular station, that maximum abundance is rarely found below fifty meters, that abundances at all levels tend to change with the change of seasons, and that certain regions more than twenty-five miles off shore are more productive of plankton diatoms than many of those near shore. Inasmuch as these observations (and most other diatom data accumulated by the Scripps Institution) are based entirely on census taking through quantitative sampling of populations, it becomes apparent that they must be based also on frustules as properties authentically representative of the organisms. This is true not only because frustules are strongly durable but also because they usually exhibit clearly the characteristics of form and aspect which distinguish the diatoms from all other organisms. Thus the frustules are placed in a position of outstanding importance in interpretation of records of abundance of living populations and of remains of populations.

It is well known that frustules of plankton diatoms are generally more delicate and thinner than those of sedentary species, differences which may be due to the necessity for suspension. Still, conditions of food supply, both qualitative and quantitative, may have a bearing. Admitting the possibility that sedentary diatoms may not be entirely free from risk of shortage of food, it still seems certain that they have far superior opportunities for obtaining essentials continuously, or almost so. Usually, it may be supposed that an excess of food supplies is available. This would tend to longer life on the part of sedentary individuals and to more thorough use of all kinds of materials, including silica for th frustules. Plankton diatoms may not hav equally good opportunities for years i some localities. Life processes must b rapid to get the most out of a transien abundance, using silica to an extent t satisfy hereditary and functional requirements only, never for extra building.

So far, the Scripps Institution has obtained no truly satisfactory informatio concerning the fate of most plankton frustules. Certain sea bottom deposits show th presence of planktonic frustules, and "diatomaceous earth" from some localities contains specimens, but in no case is the abundance sufficient to account for all frustule developed in the enormous populations occurring sometimes in many seas. Mos bottom deposits, fossil or recent, appear t contain a preponderance of the heavie walled, sedentary forms of frustules. Under the circumstances, therefore, it is natural to suppose that the thin walled plankton frustules tend to be dissolved in sea water if kept in suspension (*e.g.* by turbulence) for a long time after the death o the cell.

At sea, the Scripps Institution usually takes at each station seven catches at depth intervals of ten meters, from the surface to sixty meters. Among the thousands accumulated thus no large catch of empty frustules has ever been found beneath or nearly beneath a dense population of diatoms at surface or other high levels. On several occasions more empty frustules than viable cells were found in large catches at or near the surface of the sea. These experiences suggest that in ordinary circumstances there is enough turbulence or other disturbance in sea water to hinder or delay the sinking of empty frustules until most are dissolved or are carried to distant regions before reaching the bottom. While the suggestion may not be satisfying, it does indicate an approach toward understanding which may be expected to improve as experience increases. It is likely to be a long time before a complete history of the frustules of plankton diatoms can be written.

Scripps Institution of Oceanography
of the University of California,
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Contribution No. 129

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THE NATIONAL ACADEMY OF SCIENCES

Water masses and currents of the North Pacific Ocean:[1] H. U. SVERDRUP. The waters of the North Pacific can be considered as made up of five distinctly different water masses above a uniform deep water and covered by a thin surface layer. Perfect static equilibrium does not exist because the density of the water varies from one region of the ocean to the other, and water masses of different density can not remain next to each other unless currents are present. The equilibrium is therefore not static but dynamic, and is maintained by the prevailing currents and the changes to which the moving waters are subjected by contact with the atmosphere and by processes of mixing. The major currents of the North Pacific have the character of a series of clockwise circulations. The north and south equatorial currents flow to the west between the Equator and latitudes 20° to 25° N, and imbedded between them in latitudes 5° to 10° N the equatorial counter current flows east. Part of the water of the north equatorial current bends north when reaching the Asiatic islands and flows along the coast of Japan as the warm Kuroshio. In latitude 35° N the current turns east, one branch continuing due east and another taking a more northerly course. The water of the former turns gradually south, the greater part joining the north equatorial current to the west of the Hawaiian Islands and completing a clockwise circulation. To the east of the Hawaiian Islands and extending to about 400 miles from the American west coast is a smaller clockwise whirl which is in part linked with the bigger one to the west. The waters of the northern branch of the Kuroshio mix with the waters of the cold Oyashio and continue to the east as the cold subarctic current of the North Pacific which flows between the south coast of the Aleutian Islands and latitude 42° N. When reaching the American west coast, part of this water bends north into the Gulf of Alaska and part bends south, flowing as the cold California Current which can be traced to about latitude 25° N. The waters of the California Current mix with equatorial water and complete the largest circuit in the North Pacific as they join the west-flowing north equatorial current.

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[1] Contributions of the Scripps Institution of Oceanography, New Series, No. 129.

Contribution No. 130

tributions from the Scripps
stitution of Oceanography
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AN ANALYSIS OF THE OCEAN CURRENTS OFF THE AMERICAN WEST COAST BETWEEN 40°N AND 40°S

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It is not possible to discuss the currents off the American west coast without first examining elation of these currents to the general circulation of the waters of the Pacific Ocean. One can ediately obtain an orientation as to the currents by studying charts showing the distribution of ce temperature because this distribution is to a great extent related to the circulation. The surface eratures in August clearly show the great difference between the eastern and the western sides of Pacific Ocean and the similarity between conditions off the coasts of South and North America. g the coast of North America a tongue of low temperature extends toward the south to about ide 25°N on the coast of Lower California. In that region a very rapid transition takes place e tropical waters of uniformly high temperature above 28°C. Along the coast of South America ilar tongue extends to the north, reaching to the equator, where a rapid transition to tropical temures is encountered. In this season, which represents the summer in the Northern Hemisphere he winter in the Southern Hemisphere, the tropical waters are found entirely in the Northern isphere.

In February, that is, during the northern winter and the southern summer, similar conditions net. The tongue of low temperature off the North American coast is less conspicuous, and the ition to high tropical temperatures is more gradual. Off South America the temperatures are what higher than in August, but the character of the distribution is the same as it was in winter. transition to the tropical temperatures takes place a little south of the equator, but in this season varm-water masses are also found mainly in the Northern Hemisphere.

An inspection of these temperature charts immediately indicates that similar currents must exist the west coast of America, that is, that conditions in the Southern and the Northern hemies are nearly mirror images, but that the cold-water masses of the South Pacific reach much to the equator than those of the North Pacific.

A further examination of the water masses based on subsurface data confirms this conclusion also gives information as to the origin of the two cold currents, the California Current in the and the Peru Current in the south. Within the upper layers of the oceans between the surface depth of about 1,000 meters one can distinguish between a number of different water masses, haracter of which depends upon the exchange of heat and water vapor with the atmosphere and the prevailing currents. To the north of about latitude 43°N we find in the North Pacific a body of water which is characterized by a low temperature and a low salinity. This water is ed by mixing between parts of the warm waters of the Japan Current *(Kuroshio)* and waters e cold current coming from the north, the *Oyashio*, and by subsequent cooling of the mixture dilution by excessive rains. These processes of mixing and dilution are so thorough that to the of the Aleutian Islands and between depths of 100 and 1,000 meters water of a temperature om 2.5°C. to 3°C. and salinity of from $33.8\,^0/_{00}$ to $34.5\,^0/_{00}$ is found over wide areas. This r flows toward the east, sending one branch into the Gulf of Alaska, where it appears as a warm nt because it comes from lower latitudes, and sending the major branch south along the American coast, where it appears as a cold current from higher latitudes. This current, which is weak and gish, flows between the coast and out to a distance of three or four hundred miles and reaches halfdown Lower California, where it encounters the Pacific equatorial water and is deflected to the As it flows south it is heated and the salinity is increased by evaporation. By mixing with quatorial water and by further heating and evaporation it is transformed into part of the waters e North Equatorial Current. Thus, the waters of the California Current are subjected to characteristic changes in temperature and salinity as they complete one large circle. It should be observ however, that only a small fraction of the water masses of the North Pacific complete this large cir and much greater masses travel in smaller circles and are not subjected to similar extreme chan

In the South Pacific Ocean entirely different conditions are met. The Antarctic Ocean is c tinuous around the globe, and the waters of that ocean flow around the Antarctic continent in largest current of all oceans, the Antarctic Circumpolar Current. Part of the Antarctic waters, ho ever, are deflected to the north, owing to the southward extent of South America, and this wa continues north along the coast of Peru. This water has a higher temperature and a higher salin than the corresponding water of the North Pacific, and when flowing toward the equator its tempe ture is gradually raised by heating and its salinity is increased by evaporation such that it is tra formed into the equatorial water mass of the Pacific. A corresponding outflow from the Pacific ta place to the Indian Ocean around Australia and between the East Indian Islands.

The general features of the currents that have been discussed so far are reflected in the faunal zo In the Southern Hemisphere the zone of temperate fauna extends nearly to the equator, but in Northern Hemisphere it extends only to about 25°N, such that the zone of tropical fauna lies off American west coast, almost completely in the Northern Hemisphere.

After this general orientation, let us turn to an examination of some of the details of the t currents, the Peru Current and the California Current. Within both currents a great abundance marine organisms is found, and the remarkable fertility of the waters, in both instances, is associa with the overturning of the upper layers, which takes place under the influence of the wind anc known as upwelling. This upwelling does not bring deep water to the surface because both off P and off California the upward motion is limited to the upper two or three hundred meters. Alo the coast of California the upwelling is a seasonal phenomenon occurring mainly in the spring a early summer, from March to July, when prevailing northwesterly winds blow, and disappearing winter; whereas off the coast of Peru the upwelling takes place the year around under the influence the always dominating southerly winds. During the period of upwelling the two currents are simi in detail. On the coast of Peru the intense upwelling appears to be localized in certain regions betw which regions are found with less intense upwelling. The *Wm. Scoresby* observations (Gunth 1936) showed that off the west coast tongues of low and high temperature alternated, tongues of l temperature extending toward the equator from the regions of intense upwelling and tongues of hi temperature extending in toward the coast. Temperature observations on the coast show that t structure is a semipermanent one because the average temperature varies along the coast, regions low temperature, that is, of intense upwelling, being separated from each other by regions of hig temperature. One may expect these variations to be reflected in the distribution of organisms.

Such a tonguelike distribution of temperature is also characteristic of the California Curr during the period of upwelling (Sverdrup and Fleming, 1941). Tongues of water of alternati low and high temperature and of dimensions comparable to those off Peru are found during the peri of upwelling in an area from Point Conception to the south of San Diego. This, again, is not isolated phenomenon, because this temperature distribution has been encountered on twelve differe cruises in four years. Thus, from March to July the two currents are nearly mirror images of ea other; and the similarity is found even when subsurface conditions are considered, because in bo instances a narrow countercurrent flows close to the coast away from the equator at depths belo 200 meters. The similarity ceases, however, in winter when no upwelling takes place along t coast of California where an inshore countercurrent is present both at the surface and at subsurf depths. This inshore countercurrent, which to the north of Point Conception is known as the Dav son Current, appears to be developed every winter. A similar countercurrent at the surface does n exist off Peru, because the general wind direction is the same throughout the year; but in the southe winter, that is, in July and August, the tongues of high temperature are better developed and reg larly bring oceanic water of high temperature in to the coast in certain regions where more or l trophic destruction of organisms follows. Similar large-scale destruction is unknown from the ornia Current, but in some years of remarkably high water-temperature kelp beds have been oyed.

On the coast of Peru other catastrophes occur at irregular intervals on account of the devel- ent of the El Niño, which represents a southward intrusion of warm tropical water. The Iiño, which develops during February to April, is probably related to as yet unpredictable ges in the circulation of the atmosphere. On a small scale it is a rather frequent phenomenon ring about ten times in a century, but occasionally it assumes large proportions and may carry ropical water as far south as past Callao, causing wholesale destruction of marine life and death illions of birds that depend upon fish. The El Niño is a phenomenon which is entirely different the annual intrusion of warm oceanic water toward the coast in July and August and has no terpart in the Northern Hemisphere.

The great number of marine organisms in the waters of the California and Peru currents has mentioned. As an illustration it may be added that during recent years four to five hundred sand tons of sardines have annually been brought to the ports of California. Figures are not able from the Peru Current, because most of the fishing is done there by the guano birds, but it een estimated that the birds annually catch at least two million tons of anchovies.

The California and Peru currents are fairly clear cut, and the available information is suffi- for an analysis of the major features. This is not the case when dealing with the equatorial its off the American west coast, which vary greatly with the seasons and are apparently subjected egular changes and for which few data are available. The Equatorial Countercurrent generally aches the American coast in about latitude 5°N where part of the water turns to the south and to the north, but the locations of the different branches change from summer to winter and ilar eddies often appear to be present. The Galapagos Islands are located in a region of strong ariable currents, which, however, are in general directed from the east and in which an abundance ganisms is present. Conditions along the coast of Central America and Mexico are not well n; but in some localities, such as in the Gulf of Panama and in the Gulf of California, upwelling, wed by great production of phytoplankton, takes place in certain seasons of the year. It is not n whether similar conditions are met in other regions; but, on the whole, the swift currents, umerous eddies, and the rapidly changing conditions should be conducive to thorough mixing ocal vertical motion, which should be expected to enhance the productivity of the water.

In conclusion, it may be of interest to examine briefly the distribution of oxygen along the west of America. A characteristic feature is that in the tropical regions the water is practically without en between depths of 200 and 800 meters. The exceedingly small oxygen content off Central ica and Mexico may have great bearing upon the distribution of benthic organisms between ma and Cape San Lucas and also in the Gulf of California, where similar conditions are encoun- In the regions where upwelling occurs, as in the Gulf of California, the oxygen-poor water be drawn close to the surface, it may flood shelf areas where the depth to the bottom is 100 meters s, and it may possibly lead to catastrophic destruction of organisms that ordinarily require water higher oxygen content.

The picture which has here been presented is fragmentary and is based on incomplete informa- but that information has been used in fashioning a consistent picture of the currents and the ographic conditions and, particularly, in pointing out the similarities and the differences between California Current and the Peru Current. Many more data are desirable in order to verify the res which have been discussed. Data from the transition region off Lower California and from ropical part of the Pacific are of particular value because the factual information from these ns is very scant. Such data are needed not only for a study of the currents but also in order to n a basis for a rational explanation of the distribution of marine organisms.

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Marston C. Sargent: The Effect of Light Intensity on the Configuration of the Photosynthetic Mechanism*:- The observations and experiments of Lubimenko (Rev. Gén. Bot. 17:381, 1905; Ann. Sci. Nat., Sér. 9, 7:321, 1908) cover most of what we know about the effect of light intensity on the configuration of the assimilatory mechanism. He found that species of plants habitually growing in sunny places have a higher maximum rate of photosynthesis, and a lower chlorophyll content than species habitually growing in the shade. Furthermore, within limits set by genetic factors, individuals of any one species grown in bright light have a lower chlorophyll content than individuals grown in reduced light. To this must be added the author's observation (Pl. Physiol. 15:275, 1940) that *Chlorella* grown in bright light has a higher maximum rate of photosynthesis than when grown in dim light.

The effect of bright light in building up this capacity for photosynthesis is not specific; that is, other factors which promote growth, such as adequate supplies of iron (Emerson, J. Gen. Physiol. 12:609, 1929), nitrate (van Hille, Rec. Trav. Bot. Néerland. 35:680, 1938), and other mineral nutrients also increase the capacity for photosynthesis. Green plants or green plant parts which are growing actively have a high capacity for photosynthesis. If growth is retarded by the absence or reduction of any necessary factor, the capacity for photosynthesis is reduced.

The fact that plants grown in very bright light have a lower chlorophyll content than individuals grown in dimmer light was accounted for by a theory of Wiesner (Sitzungsber. Akad. Wiss. Wien, Math.-Naturw. Kl. 69:379, 1874). He proposed that both the formation and decomposition of chlorophyll proceed simultaneously under the influence of light and that the effect of increasing light intensity is to increase the rate of decomposition more than the rate of formation. The author (*l.c.*) showed in the case of cultures of *Chlorella* that although the chlorophyll content is lower in plants grown in bright light, the rate of formation of chlorophyll, not only by a culture, but also by a single cell, is higher. The chlorophyll content remains low because the rate of production of cell material is also high. The same processes can occur in leaves. The rate of production of chlorophyll may be twice as great in the sun as in the shade, but if the rate of production of leaf material is three times as great, the chlorophyll content will remain low. It is not to be expected that these relationships will hold to the end of the life cycle of a leaf when disturbing processes begin, but only during the period of active growth. If a series of careful observations confirm this hypothesis Wiesner's theory, while not disproved, will become unnecessary.

Scripps Institution of Oceanography,
La Jolla, California. *February 1941.*

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[1] In Russland wird sie seit mehr als 90 Jahren .B. von German, Palimpzestev (1889), V. Taliev (1902) vertreten, aber von den grossen Mehrzahl der Steppenforscher abgelehnt. (Anm. von H. Gams).

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SCRIPPS INSTITUTION OF OCEANOGRAPHY,
LA JOLLA, CALIFORNIA. *February 1941.*

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Contribution No. 132

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COMPARATIVE STUDIES OF THE PIGMENTS OF SOME PACIFIC COAST ECHINODERMS[1]

DENIS L. FOX AND BRADLEY T. SCHEER

(*From the Scripps Institution of Oceanography, La Jolla, California*)

From the standpoint of comparative biochemistry, the echinoderms represent an interesting and little-explored phylum. Prominent among the biochemical features of this group is the conspicuous manifestation of body-pigments, striking in their intensity and color-varieties, and rivalling the beauty of those displayed by the sessile coelenterates.

The integumentary colors of sea-stars and brittle stars are due preponderantly to carotenoids, while certain of the echinoids manifest instead considerable quantities of pigments of the echinochrome class, first reported by MacMunn (1883*a*) and recently shown by Kuhn and Wallenfels (1939) to be naphthoquinones. Kuroda and Ohshima (1940) have crystallized three distinct spinochromes, each from a different species of Japanese sea-urchin, and have found the natural pigments to be very similar to synthetic hydroxynaphthoquinones. Some echinoids yield echinenone, a unique carotenoid which is a provitamin A (Lederer and Moore, 1936). Long ago, MacMunn (1883*b*, 1886) reported the presence of " enterochlorophyll " in the alimentary organs of a number of carnivorous echinoderms.

Studies of Abeloos (1926) and Lönnberg (1931, 1932, 1933) give qualitative indications of the nature and distribution of carotenoids in echinoderms. Euler and Hellström (1934) and Euler, Hellström and Klussman (1934) made chemical studies of the carotenoid proteins of asteroids, and isolated a new pigment, asteric acid. Karrer and Benz (1934) and Karrer and Solmssen (1935) isolated astacene from both an ophiuran and an asteroid. Lederer (1938) has studied the pigments of the echinoid *Strongylocentrotus lividus*.

Numerous writers emphasize the importance of the question as to whether some of the lower animals may be able to synthesize specific carotenoids from simpler molecules. Among the various ecological factors and physiological activities which may influence the pigmentation of animals, it is probable that food exerts the closest and most direct effect, although habitat and various physiological adaptations inseparably associated with nutrition are necessarily important in a survey such as we have undertaken.

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 132.

Of the rather scanty information available regarding the physiology of adult echinoderms, facts concerning their feeding mechanisms and digestive enzymes are probably the chief entries. Yonge (1928) discusses the diversity of feeding mechanisms employed by the Echinodermata, and divides the phylum into two main groups as regards feeding and digestion, namely: (1) the Asteroidea and Ophiuroidea which are exclusively carnivorous, and (2) the Echinoidea and Holothuroidea, chiefly herbivorous and to some extent omnivorous. He suggests (1931) that the ciliary-feeding Crinoidea may be primarily herbivorous.

In the present study, we have attempted to make a preliminary classification of the various echinoderms into biochemical (pigment) types, with correlative differences in intraphylar class, sex (where practicable), habitat and nutritional habits occupying collateral positions of importance.

The survey, which included four species of three genera of echinoids, one species of holothuroid, four species of three genera of asteroids, and three species of two genera of ophiuroids, revealed numerous familiar and a few new carotenoids. Purple echinochrome pigments were observed only in echinoids. Small amounts of green " enterochlorophylls " were found among the asteroids and ophiurans. We have considered the echinoderm classes in ascending evolutionary series within the two chief nutritional groups named by Yonge (1931) i.e. (1) herbivore-omnivores: (a) echinoids, (b) holothuroids; and (2) carnivores: (a) asteroids, (b) ophiurans. Consistencies in this classification will be apparent in Table I.

The animals were collected at several localities in this vicinity of the Southern California coast, and in some cases obtained by dredge hauls. We are indebted to Mr. P. S. Barnhart, curator, Dr. C. E. Moritz, visitor from Dartmouth College, Professor G. E. MacGinitie of the California Institute of Technology, Mr. Granville Ashcraft of the Hancock Foundation, University of Southern California, Professor H. J. van Cleave, visitor from the University of Illinois, and Mr. L. D. Pratt of the Kelco Company, National City, for much of the material used. Mr. Sheldon C. Crane rendered technical assistance during the latter part of our carotenoid investigations.

METHODS

With but few exceptions noted below, the animals were placed temporarily in running sea water in laboratory aquaria, to permit foreign material to be evacuated from the intestine. The carotenoid pigments were extracted from the ground tissues with acetone, passed into petroleum ether, subjected to partition between the latter and 90 per cent methanol, and separated into individual components by chromatographic adsorption, in accordance with regular procedures described in more detail by Scheer (1940) and by Fox and Pantin (1941).

Individual pigments were provisionally identified by comparison of certain of their properties with those of known pigments; this identification must wait upon further studies for full confirmation. The following properties were used: (1) Behavior in partition between immiscible solvents, i.e., petroleum ether (which constitutes the epiphase and dissolves carotenes, xanthophyll esters and a few monohydroxyxanthophylls) and 90 per cent methanol (the hypophase which selectively removes xanthophylls). (2) Adsorption behavior on Tswett chromatographic columns, xanthrophylls and their common esters being adsorbed from benzene solution on calcium carbonate, while carotenes pass through this but are selectively adsorbed on calcium hydroxide (Zechmeister and Cholnoky, 1937; Strain, 1938). (3) Positions of spectral absorption maxima. (4) Behavior toward the partition test after treatment with hot alcoholic potassium hydroxide in an inert atmosphere; carotenes remain unchanged; xanthophylls, epiphasic when esterified, are rendered hypophasic when hydrolyzed; astaxanthin, free or esterified, neutral before treatment, is transformed into astacene, with definite acidic properties.

Positions of absorption maxima were determined with a Hartridge reversion spectroscope and with a Bausch and Lomb spectrophotometer. The two instruments show good agreement excepting in the case of acidic carotenoids like astacene, whose single broad maximum is more accurately determined with the latter instrument. Carbon disulphide was employed as the solvent unless otherwise specified.

Relative concentration of mixed carotenoid pigments (i.e., whole epiphasic or whole hypophasic fractions) were estimated in terms of "β-carotene equivalents," the extinction coefficient of β-carotene at 485 mμ being determined by other writers (Smith, 1936) and ourselves.

Echinochrome pigments were readily extractable from the echinoids by treatment of the whole tests with dilute hydrochloric acid under a layer of diethyl ether which readily dissolved the pigments (see Tyler, 1939). These were subsequently examined spectroscopically in ether or chloroform solutions.

Green pigments ("enterochlorophylls") were recovered in small amounts from the digestive diverticula of two of the asteroids, *Pisaster ochraceous* and *P. giganteus,* and from the whole-body extracts of all three ophiurans. The material recovered from the ophiurans differed in certain solubility properties from that yielded by the asteroids, but all showed closely agreeing absorption spectra. Actual quantities were so small that no identifying tests were practicable excepting those employed; hence the descriptive term coined by MacMunn has been used provisionally in the discussion of these green pigments.

Results

A summary of the distribution of carotenoids, echinochromes and enterochlorophylls is given in Table I, followed by more detailed information regarding the separate pigments.

Carotenoids

The distribution, kinds, and some relative quantities of individual carotenoids encountered in the various species are summarized in Table II.

Echinochromes

These pigments, present exclusively in the echinoids, showed a few interesting variations in tissue distribution as well as in chemical and spectroscopic properties, as shown in the following outline:

Dendraster excentricus: Purple aggregates of the pigment were present in ectodermal and endodermal tissues lining the shell of this purple sand-dollar, while similar bodies in mature male and female gonad tissues and in anterior portions of the gut were red. The posterior part of the gut lacked echinochrome. The gelatinous egg-cases contained red echinochrome bodies.

The pigment was purple in neutral or alkaline media and red in acid (see also Lederer, 1940). It was readily soluble in aqueous acetone, giving clear filterable solutions, and was also extractable from dilute acid digests of the shell with diethyl ether (see Tyler, 1939).

The absorption maxima were as follows:

In acetone: 524, 490 mμ.

In chloroform: 533, 496, 465 mμ (*cf.* Kuhn and Wallenfels, 1939).

Strongylocentrotus franciscanus: Much purple pigment was yielded to acetone by treatment of this large purple-red urchin. The pigment decomposed with bleaching, however, before it was given any study.

Strongylocentrotus purpuratus: This purple urchin, like the sand-dollar *Dendraster,* showed many aggregates of echinochrome in the ectoderm (purple) as well as in endoderm, coelomic fluid and gut wall (red in all). Neither male nor female gonad tissues, however, contained any of the pigment.

It showed the following absorption maxima:

In water (neutral, colloidal): 526.5, ~~5~~491 mμ.

In water (acidic): 497 mμ (single, diffuse band).

In chloroform: 525, 490.5 mμ (*cf.* Lederer and Glaser, 1938).

Lytechinus pictus: This pale urchin yielded far less of the purple pigment than did *Strongylocentrotus* or even *Dendraster.* Pigment aggregates were observable, however, in parts of the skin lining the shell, in the gut and in gonad tissues of both sexes.

The pigment, insoluble in acetone or water, readily bleached by alkali, and slightly soluble in dilute acid, gave the following spectral absorption bands:

In water (colloidal suspension): 526, 491 mμ.

In diethyl ether: 533, 497, 467 mμ.

The echinoids contained not only different quantities of echinochrome pigments, in the order *Strongylocentrotus* > *Dendraster* > *Lytechinus,* but the pigments were somewhat different chemically. Lederer (1940) lists the distribution of a number of pigments of the echinochrome class in several echinoid species, and in their separate body parts.

Green Pigments

The "enterochlorophylls," found only in the digestive diverticula of two of the five species of asteroids and in whole extracts of the three ophiuroids, showed certain chemical differences.

Asteroidea

Pisaster ochraceous: A small quantity of the pigment was recovered in acetone from the digestive diverticulum, being absent from stomach, skin or other parts. Completely insoluble in petroleum ether, it was readily soluble in alcohol, acetone and diethyl ether. Its non-acidic character was demonstrated by its extractability from diluted alkaline alcohol with ether. Dissolved in absolute ethanol, it manifested a single sharp absorption band in the red at 661 mμ.

Pisaster giganteus: The green pigment in this species, recovered in traces from the same tissues as in *P. ochraceous,* was similar in its chemical properties and also yielded a single absorption band in pure ethanol at 661 mμ.

Astropecten californicus and *Patiria miniata* failed to yield green pigments.

Ophiuroidea

Ophiopteris papillosa: Extracted with acetone and soluble also in diethyl ether, the pigment was dissolved readily in petroleum ether (un-

Table I

Summary of Pigments in Echinoderms Studied

Animal (number analyzed)	Tissue; weight grams	Total epiphasic carotenoids mg./100 g.	Total hypophasic carotenoids mg./100 g.	Ratio; hypophasic/epiphasic	Carotenes	Xanthophylls	Xanthophyll esters	Acidic carotenoids or their precursors	Predominating *types* of carotenoid	Echinochromes	"Enterochlorophylls"
HERBIVORES; OMNIVORES											
ECHINOIDEA											
Dendraster excentricus											
(3 ♀)	whole; 31	0.052	0.011	0.211	++	+	–	...	β-carotene	+	–
(2 ♂)	whole; 20	0.105	0.038	0.362							
Strongylocentrotus franciscanus (1 ♂)	whole; 298	0.170	0.025	0.147	++*	+	–	...	β-carotene	+	–
S. purpuratus											
(3 ♀)	skin ...	traces	traces	...			± (varying)	–	zeaxanthin, β-carotene.	+	–
	intestine; 5.67	2.99	6.04	2.02	++*	++					
	gonad; 8.64	2.00	0	0	++*	–					
(3 ♂)	skin ...	traces	traces	...							
	intestine; 4.72	2.34	5.65	2.41	++*	++					
	gonad; 11.9	0.690	0	0	++*	–					
Lytechinus pictus											
(26 ♀)	whole; 131	0.493	0.351	0.712	++*	+	–	...	α- and β-carotenes, echinenone.	+	–
(13 ♂)	whole; 67	0.871	0.430	0.493							
(9 ♀)	intestine; 0.9	4.48	4.18	0.934	++	+					
	gonad; 2.6	0.862	0.283	0.328	++	+					
	test; 27.0	0.009	0.012	1.33	traces	traces					
(11 ♂)	intestine; 1.6	3.38	1.52	0.450	++	+					
	gonad; 5.3	4.48	0.528	0.118	++	+					
	test; 47.0	0.012	0.013	1.18	traces	traces					
HOLOTHUROIDEA											
Stichopus californicus											
(3)	whole; 127	0.013	0.010	0.769	+*	+	–	...	echinenone, pectenoxanthin.	–	–
(1)	whole; 58.0 (eviscerated)	0.015	0.021	1.40							

Animal (number analyzed)	Tissue; weight grams	Total epiphasic carotenoids mg./100 g.	Total hypophasic carotenoids mg./100 g.	Ratio; hypophasic / epiphasic	Carotenes	Xanthophylls	Xanthophyll esters	Acidic carotenoids or their precursors	Predominating *types* of carotenoid	Echinochromes	"Enterochlorophylls"
CARNIVORES											
ASTEROIDEA											
Astropecten californicus (17)	whole; 70.0	0.044	0.718	16.3	+*	+++	—	+	pectenoxanthin, astaxanthin.	—	—
Patiria miniata Color varieties (*a*) ochraceous buff, carmine, Indian purple (1)	whole; 176	0.028	0.434	15.5	+	+++	—	+	zeaxanthin, astaxanthin.	—	—
(*b*) scarlet, scarlet orange (1)	whole; 195	0.079	1.29	16.3	+	+++	—	+	zeaxanthin, astaxanthin.	—	—
Pisaster ochraceous Color varieties (*a*) Rufous (1)	2 rays+skin; 114	0.022	0.204	9.28	+	+++	—	+	zeaxanthin, astaxanthin, mytiloxanthin.	—	—
	pyloric caeca; 52	0.667	12.9	19.3	+	+++	—	+			+
(*b*) Chocolate (1)	2 rays+skin; 85	0.024	0.284	11.8	+	+++	—	+		—	—
	pyloric caeca; 13	0.455	9.01	19.8	+	+++	—	+			+
Pisaster giganteus (1)	2 rays+skin; 62	0.067	0.902	13.4	+	+++	traces	+	zeaxanthin, astaxanthin or metridene.	—	—
	pyloric caeca; 10.4	0.401	1.37	3.41	+	++	traces	+			+
OPHIUROIDEA											
Ophiopteris papillosa (4)	whole; 9.81	0.489	2.90	5.95	—	+++	+	?	taraxanthin, pectenoxanthin.	—	+
(53)	whole; 102	0.254	decomp.	(hypo. > epi.)							
Ophiothrix spiculata (35)	whole; 18	1.60	decomp.	(hypo. > epi.)	—	+++	+	+	taraxanthin; new xanthophylls.	—	+
Ophiothrix rudis (18)	whole; 8.8	1.40	decomp.	(hypo. > epi.)	—	+++	+	+	taraxanthin; new xanthophylls	—	+

* and echinenone.

TABLE II

Summary of Carotenoids in Echinoderms Studied

Animal	Epiphasic fraction (carotenes, esters)				Hypophasic fraction (xanthophylls, acidic carotenoids)			
	Chromatogram:				Chromatogram:			
	Total number of zones	Descending order of *principal* zones	Absorption maxima mμ	Corresponding known pigments	Total number of zones	Descending order of *principal* zones	Absorption maxima mμ	Corresponding known pigments
Dendraster excentricus	—	—	521; 484 (whole fraction)	β-carotene	—	—	518; 483 (whole fraction)	zeaxanthin
Strongylocentrotus franciscanus	6	II III IV	525; 488 520; 484 520; 484	echinenone β-carotene β-carotene	3	I (II) (III)	510; 479 511; 478 (whole fraction)	lutein lutein (isomers)
Strongylocentrotus purpuratus	5 to 9	I II III IV V	506; 478 — — 490 518; 483 510.5; 479.5	lutein *ester* echinenone β-carotene α-carotene	3 to 6	I II III	511; 481 511; 481 to 484 515; 480 to 484	petaloxanthin or antheraxanthin? zeaxanthin
Lytechinus pictus	3 to 7	I II III IV	490 519; 484 } 519; 486 } 507; 477	echinenone β-carotene α-carotene	4 to 5	I II III	512; 482 511; 479 509; 477	petaloxanthin or antheraxanthin lutein
Stichopus parvimensis	5	(combined extract)	521; 489	echinenone	4	(combined extract)	521; 489	pectenoxanthin?
Astropecten californicus	4	IV	519; 485	β-carotene	5	I II III	510; 481 505 (hot KOH →acid) 520; 489	antheraxanthin astacene or metridene pectenoxanthin
Patiria miniata	3 to 6	(combined extract)	—; 482 to 485	β-carotene (?)	4 to 6	II III	507 to 509 (hot KOH →acid) 517 to 521; 483 to 484	astaxanthin → astacene zeaxanthin

TABLE II—*Continued*

Animal	Epiphasic fraction (carotenes, esters)				Hypophasic fraction (xanthophylls, acidic carotenoids)			
	Chromatogram:		Absorption maxima mμ	Corresponding known pigments	Chromatogram:		Absorption maxima mμ	Corresponding known pigments
	Total number of zones	Descending order of *principal* zones			Total number of zones	Descending order of *principal* zones		
Pisaster ochraceous	—	—	— —	carotene(s)	5 to 7	I II III	502 to 505 (acidic) 506 to 510 (hot KOH →acid) 514 to 520; 483 to 485	mytiloxanthin astaxanthin→ astacene zeaxanthin
Pisaster giganteus	6	(combined extract)	510; 483 519; 484	zeaxanthin *ester* β-carotene	5 to 7	I II III	516; 482 505; (495 in pyridine) (hot KOH→acid with same spectra) 513 to 518; 485 to 486	antheraxanthin metridene zeaxanthin
Ophiopteris papillosa	5	II III	497; — 505; — whole; 502; 471	esters taraxanthin *ester*	4	I II III IV	501; 470 503; 468 506 (not rendered acidic by hot KOH) 522; 489	taraxanthin a new xanthophyll? pectenoxanthin
Ophiothrix spiculata	11 or more	IX X XI	466 475 499; 466; 434	new acid on hydrolysis new acid on hydrolysis new xanthophyll *ester*	5	I II	495; 467 505	new xanthophyll new xanthophyll
Ophiothrix rudis	5	II V	505 460 whole; 497; 466 (before hydrolysis)	new acid on hydrolysis new acid on hydrolysis xanthophyll esters	more abundant than epiphasic fraction, but decomposed too rapidly for analysis			

like those encountered in the asteroids) but migrated quantitatively from this solvent to 90 per cent methanol in the partition test. It was adsorbed from petroleum ether solution at the top of a calcium carbonate column and was eluted therefrom with difficulty by methanol and acetic acid. Its solution in absolute ethanol gave a single band in the red at 663 mμ.

Ophiothrix spiculata: A yellow-green pigment remained in the diluted and salt-containing acetone extract from which all carotenoids had been transferred to petroleum ether. Insoluble in the latter solvent, even in the presence of dilute acids, this pigment was readily extracted with diethyl ether and transferred to absolute ethanol, in which it showed a single absorption band at 663 mμ.

Ophiothrix rudis yielded small quantities of a green pigment similar in solubility properties to that recovered from *O. spiculata.*

MacMunn's green pigments extracted from the radial caeca of *Solaster* and *Uraster* displayed several spectral bands in alcohol solution, one in the vicinity of a single band found in the red by ourselves, and the others in additional regions similar to those shown for chlorophyll. He considered that such green pigments were breakdown products of chlorophyll (MacMunn, 1886).

We have at present no new suggestions to add to MacMunn's conclusions. While the spectra of our green pigments were far simpler than those of MacMunn or than those of chlorophyll, it is likely that these pigments in the digestive organs of carnivores represent porphyrins from an *original* source of chlorophyll.

Discussion

The major results obtained in this study are summarized in Table I. The animals are grouped according to their food habits. The echinoids feed on kelp, on detritus that is predominantly of vegetable orgin, or upon fixed algae, while the holothurians are bottom dwellers that subsist on the latter two classes of food. The asteroids feed exclusively on animal matter, especially mollusks, while the ophiuroids feed mainly on very small particulate animal matter.

A few calculations based upon information given in Table I reveal some interesting qualitative and quantitative differences between the carotenoids of herbivores and those of carnivores. For example, a total weight of 847 grams of tissue from herbivorous forms yielded some 4.27 mg. of carotenoid pigment (β-carotene equivalents), or an average concentration of about 0.50 mg. per 100 grams of fresh tissue. In the carnivores, on the other hand, 916 grams of tissue yielded a measurable quantity of some 14.61 mg. of carotenoids (β-carotene equivalents), giving an average concentration of about 1.60 mg. per 100 grams of fresh tissue. The average ratios of hypophasic to epiphasic pigments were, in the herbivores, 0.86, and in the carnivores, at least 13. Furthermore, account is to be taken of the fact that the hypophasic pigments in the ophiuroids were, as in the other carnivores, far in excess of the epiphasic ones, but that, in three out of four analyses, the color of the hypophasic fraction bleached before quantitative estimations could be made. If we assume that the hypophasic pigments in the second catch of *Ophiopteris papillosa* exceeded the epiphasic fraction by the same ratio as was found in the first catch (i.e. about 6) and that this ratio could be applied also to the other two ophiuroid species, *Ophiothrix spiculata* and *O. rudis,* we then arrive at a figure of 2 mg. of carotenoids per 100 grams of fresh carnivore tissue.

Among the carnivores, the ophiuroids contained oxygenated carotenoids exclusively, the epiphasic fractions yielding no carotenes, but only esterified xanthophylls and acidic carotenoids. The asteroids likewise showed a great preponderance of oxygenated over hydrocarbon carotenoids. *Pisaster giganteus* contained an epiphasic esterified xanthophyll which behaved like zeaxanthin. In the herbivores, the echinoids too contained some xanthophyllic pigments without exception, and most of them yielded an oxygenated carotenoid, echinenone, in the epiphasic fraction. One of three catches of *Strongylocentrotus purpuratus* yielded an esterified xanthophyll resembling lutein.

In summary, carnivorous species contained three to four-fold the quantity of carotenoid pigments found in herbivores. The oxygenated type of carotenoid, including xanthophylls and acidic compounds, preponderated vastly over carotenes [2] in carnivorous species. However, the herbivores, with the exception of the urchin *Strongylocentrotus purpuratus* which showed a slight excess of xanthophylls over carotenes, possessed predominating quantities of the latter type of pigment. Finally, the non-hydrocarbon carotenoids stored in carnivorous animals were more heavily oxygenated than those in the herbivores, the former yielding numerous carotenoid acids, as well as taraxanthin and similar xanthophylls, none of which were encountered in any of the herbivores.

The apparently greater capacity of the carnivorous, as compared with the herbivorous echinoderms, to assimilate or store carotenoids, with perhaps a certain degree of oxidative modification, may be associated with less metabolic utilization of the oxidized pigments than of the carotenes. At present nothing seems to be known either of the requirements of marine invertebrates for vitamin A or its precursors, or of specific rôles played by carotenoids in lower phyla.

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[2] It should be understood that the term "carotenes" as used here means those epiphasic pigments resistant to alkaline hydrolysis, and hence may include such mono-hydroxy xanthophylls as cryptoxanthin and the ketone echinenone. The possible presence of cryptoxanthin was usually eliminated, however, by employing in the partition test 95 per cent methanol, in which this pigment is preferentially soluble.

The carotenoid acids are of especial interest and may be classified into three types. *In vivo* some are neutral xanthophylls but treatment with alcoholic alkali produces molecular rearrangements and oxidations which lead to the formation of acids (*cf.* astaxanthin). This type was found only in the asteroids but was present in all such specimens examined. The second type is acidic as it is extracted from the tissues. It was found only in *Pisaster,* and since it resembles strongly the mytiloxanthin described by Scheer (1940) from the California mussel, it is likely that *Pisaster* derives this pigment from the mollusk, upon which it feeds extensively. Finally, acids may occur *in vivo* as esters, in which case they are epiphasic before hydrolysis, their acidic properties becoming evident after treatment with alcoholic potash. These esters were found only in ophiurans and gave on hydrolysis a new type of pigment, which is acidic, and has a single absorption maximum at 460, 466 or 475 mμ. In addition, an acid-yielding ester of the more conventional type with a single absorption maximum at 505 mμ appeared.

As in the lobster, carotenoid acids were found to be combined with protein in one case. *Pisaster giganteus* contains purple, blue and yellow chromoproteins in the skin, the purple and blue patches of which yielded an unesterified carotenoid, which formed an acid on treatment with alkali. This pigment resembled the anemone pigment metridene (Fox and Pantin, 1941).

Table II shows some similarities between certain of the echinoderm carotenoids and known pigments. A commonly occurring one showed a spectrum like that of β-carotene or zeaxanthin; pigments in this group were found in all classes except the Ophiuroidea, which yielded instead pigments with spectra like taraxanthin, not found in the other classes. Spectra like that of α-carotene or lutein were not frequently encountered, except among the echinoids, wherein both carotenes and xanthophylls with this type of spectrum were found. Pigments resembling echinenone have been mentioned above, notably in the epiphase of echinoid extracts (Lederer, 1938). The unchromatographed extracts, both epiphasic and hypophasic, of *Stichopus* also showed the echinenone type of spectrum; again the alkali-resistant epiphase and the hypophase of one of the carnivores, i.e., *Astropecten,* as well as certain hypophasic pigments (rare xanthophylls such as pectenoxanthin) in other groups, manifested the same absorption maxima.

Where individual tissues were studied, the highest values were found in the digestive tract, excepting in the testes of *Lytechinus;* certain asteroid skins would also show relatively high values were they readily separable from the colorless skeleton.

The few correlations which could be observed between sex and carotenoid content in tissues were limited to three of the echinoid species. In *Dendraster,* males contained about twice the concentration of epiphasic and thrice the hypophasic pigments found in females. Estimations of pigments in individual tissues were not made. In *Strongylocentrotus purpuratus,* the skin of each sex yielded only traces of carotenoids. In the intestine, epiphasic pigments were plentiful and of the same order of concentration in both sexes; the same was true of the hypophasic compounds. However, carotenoids in ovaries exceeded those in testes by three-fold, and were entirely epiphasic, xanthophylls being absent. In *Lytechinus,* whole males yielded somewhat more of each class of carotenoid than did whole females. This was due to a five-fold excess of epiphasic and nearly a two-fold excess of hypophasic carotenoids in testicular over ovarian tissues. Intestines, considerably lighter in mass than gonad material, were also fairly rich in pigment, females yielding nearly a third again as much epiphasic and almost three times as much hypophasic pigment as males. The skin of *Lytechinus,* like that of *Strongylocentrotus,* contained only traces of carotenoids.

Females of *Strongylocentrotus* and *Lytechinus* contained some 25 and 27 per cent, respectively, of their carotenoids in the ovaries, whereas corresponding males mobilized approximately 17 and 77 per cent, respectively, to their testes, although the sperm itself was not colored.

The carotenoid distribution ratio between intestine and ovary is doubtless subject to variation with discharge of ripe eggs. There still remains the striking mobilization of carotenoids to testicular tissues, especially in *Lytechinus.* Also remarkable was the complete absence of xanthophylls from the gonads of both sexes of *Strongylocentrotus.*

Three types of non-carotenoid pigment were encountered in this study. Insoluble pigments, presumably of the melanin type, appeared in *Stichopus* and *Pisaster ochraceus,* but were not studied. Green pigments, the "enterochlorophylls" of MacMunn, were obtained from certain of the carnivores, but were never found in starved herbivores. These pigments invariably had absorption maxima at 661 and 663 mμ in absolute ethanol. From all the echinoids, but from no others, much red to purple pigment of the echinchrome type was extracted. It was found as calcium salt in the testes and spines, and as purple (basic) or red (acidic) irregular bodies dispersed in the tissues of ectoderm, endoderm, intestine, and in some cases, in the gonads. Although quantitative studies were not made, echinochrome was clearly most abundant in *Strongylocentrotus,* quite abundant in *Dendraster,* and present in relatively small amounts in *Lytechinus.*

In conclusion it may be reiterated that the echinoderms represent a structurally and ecologically diverse group of much interest for further investigations of a comparative biochemical nature, especially regarding the metabolism of colored compounds.

SUMMARY

1. The pigments of echinoderms, belonging to twelve species, nine genera and four classes, have been studied qualitatively and in part quantitatively, with the aid of certain standard methods.

2. Carnivorous species contained more carotenoids in the aggregate than did herbivores, by some three or four-fold.

3. Among the echinoids, *Dendraster* and *Lytechinus* males yielded more total carotenoids than did females, while in *Strongylocentrotus purpuratus,* the concentrations in each sex were similar. Females of *Strongylocentrotus* and *Lytechinus* contained about a fourth of their carotenoids in the ovaries, whereas corresponding males mobilized about one-sixth and three-quarters, respectively, to their testes.

4. Oxygenated carotenoids, including xanthophylls and acidic compounds, preponderated vastly over the hydrocarbon type (carotenes) in carnivores, while in most herbivores epiphasic pigments, including carotenes and echinenone, showed some degree of predominance.

5. The presence of the ketonic carotenoid echinenone was indicated in most of the echinoids; its presence was also regarded as likely in another member of the herbivore-omnivore group, i.e., the cucumber *Stichopus,* and in one carnivore, *Astropecten.*

6. Carotenoid acids, or compounds which yield carotenoid acids on treatment with alkali, were found only in carnivorous species. A new type of epiphasic pigment, with a single absorption maximum in the violet at values of from 460 to 475 mμ, yielding an acid on hydrolysis, was found in the ophiuroids.

7. Xanthophyll esters were found consistently in the Ophiuroidea and in one of the Asteroidea, *Pisaster giganteus.* In the ophiuroids, they were of the heavily oxygenated type, and replaced carotenes, which were completely lacking. One of three catches of *Strongylocentrotus purpuratus* yielded some esterified lutein-like xanthophyll.

8. The occurrence of echinochromes, found only in the echinoids, and of green pigments, "enterochlorophylls," found in the intestines of carnivores, is discussed.

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Contribution No. 133

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THE INFLUENCE OF BOTTOM TOPOGRAPHY ON OCEAN CURRENTS

By

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Scripps Institution of Oceanography of the University of California

NEW SERIES, NO.133

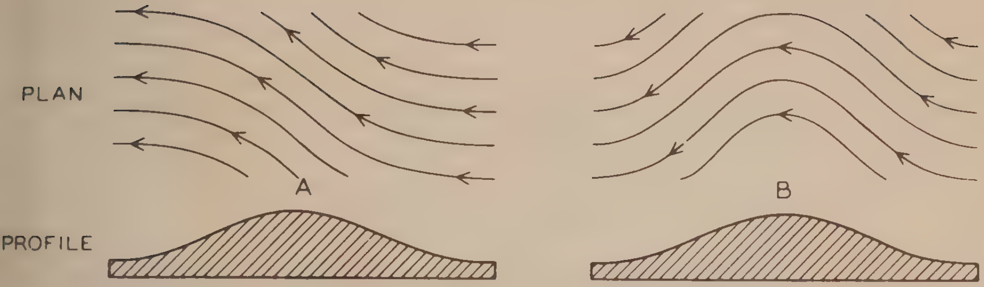
ABSTRACT

The modifications are examined to which an ocean current related to the distribution of density is subjected when flowing across a submarine ridge. It is shown that the current is bent to the right in the Northern Hemisphere, and in the Southern Hemisphere to the left, the maximum deviations from a straight course occurring over the ridge. The result is only qualitatively correct. A steady state cannot exist, wherefore irregular eddies are probably superimposed on the simple pattern of flow.

INTRODUCTION

Ekman[1] has examined the effect of the bottom topo-
hy on currents in homogeneous water. He found that
g to the earth's rotation the currents would tend to
east-west near the Equator, but in high latitude
would tend to follow the bottom contours. In a
ent flowing uphill from deeper into shallower water,
effect of the bottom friction would be to bend the
ent to the right in the Northern Hemisphere and to
left in the Southern Hemisphere, and the curvature of
current would be proportional to the slope. Where
flow was downhill the current would curve in the
site direction. A symmetrical submarine ridge should
efore deflect a straight current as shown in Fig. 1A,
oceanographic data indicate that the observed de-
tions have more the character illustrated in Fig. 1B.
ill be shown that the latter type of deflection can
ccounted for by considering that ocean currents are
ely related to the distribution of density, which is
nction of salinity, temperature, and pressure.

It is not possible to analyze exactly the effect of
om topography on ocean currents which are related to
distribution of the density of the water, but some
itative conclusions can be drawn by means of certain
tionships between the fields of mass, pressure, and
city in the sea.



ig. 1. Deflections of a horizontal ocean current which
crosses a submarine ridge, as shown in the profiles
below the plans. A. Deflection caused by bottom
friction (according to Ekman). B. Deflection
caused by altered distribution of density.

ANALYSIS

Assuming that accelerations and frictional forces are
all, the equations of motion as applicable to ocean cur-
nts are reduced to

$$\rho 2\omega \sin\varphi v - \frac{\partial p}{\partial x} = 0 \qquad (1)$$

$$\rho 2\omega \sin\varphi u + \frac{\partial p}{\partial y} = 0 \qquad (2)$$

$$g\rho - \frac{\partial p}{\partial z} = 0 \qquad (3)$$

rectangular coordinate system is used with the vertical
is taken positive downwards. Here ρ is the density of
e water, ω is the angular velocity of the earth, φ the
titude, u and v the horizontal velocity components, p
e pressure, and g the acceleration of gravity. Eqs.
) and (2) state that the horizontal pressure gradient
balanced against Coriolis' force and, according to
. (3), the vertical component of the velocity is neg-
gible, wherefore the equation of static equilibrium
satisfied in the sea.

By means of the equations of isobars and isopycnals
a vertical plane, other relations can be established.
e equations of isobars and isopycnals in the x-z plane
e

$$\frac{\partial p}{\partial x} dx + \frac{\partial p}{\partial z} dz = 0 \qquad \text{and} \qquad \frac{\partial \rho}{\partial x} dx + \frac{\partial \rho}{\partial z} dz = 0$$

From these one obtains the slopes of the isobars and isopycnals:

$$i_p = \left(\frac{dz}{dx}\right)_p = -\frac{\partial p/\partial x}{\partial p/\partial z} \tag{4}$$

$$i_\rho = \left(\frac{dz}{dx}\right)_\rho = -\frac{\partial \rho/\partial x}{\partial \rho/\partial z} \tag{5}$$

These slopes are positive downwards because the positive z-axis is directed downwards.

From Eqs. (3) and (4) follows

$$g\rho i_p = -\frac{\partial p}{\partial x} \tag{6}$$

and from Eqs. (3), (5), and (6) one obtains

$$\frac{\partial}{\partial z}(\rho i_p) = i_\rho \frac{\partial \rho}{\partial z} \tag{7}$$

Assume that one isobar, defined by $p = p_2$, is horizontal, and integrate Eq. (7) between the depths at which the pressure is p_1 and p_2, respectively, where $p_1 < p_2$. The result is

$$(\rho i_p)_1 = -\bar{i}_\rho(\rho_2 - \rho_1) \tag{8}$$

where $\bar{i}_\rho$ is the average inclination of the isopycnals in the layers under consideration. Placing the y-axis of the coordinate system parallel to the isobars, one obtains from Eq. (2) $u = 0$, and from Eqs. (1), (6), and (8)

$$v = -\frac{1}{2\omega\sin\varphi}\, g i_{p_1} = \frac{1}{2\omega\sin\varphi}\, g\bar{i}_\rho\left(\frac{\rho_2-\rho_1}{\rho_1}\right) \tag{9}$$

Eqs. (8) and (9) express the relations between the fields of mass, pressure, and velocity which must exist on the assumptions which have been made, and which appear to be approximately fulfilled when dealing with ocean currents. Eq. (8) is generally valid but in Eq. (9) the signs must be reversed if the equations are to be applied to currents in the Southern Hemisphere.

The added assumptions that the density of the moving water remains constant and that the fields are stationary impose further conditions on the system. Because the vertical component of the velocity is negligible, stationary distribution of pressure and mass ($\partial p/\partial t = 0$ and $\partial \rho/\partial t = 0$)

exist if

$$\frac{\partial p}{\partial x}u+\frac{\partial p}{\partial y}v=0 \qquad \text{and} \qquad \frac{\partial \rho}{\partial x}u+\frac{\partial \rho}{\partial y}v=0$$

The first equation is fulfilled according to Eqs. (1) and (2), by means of which the second equation leads to

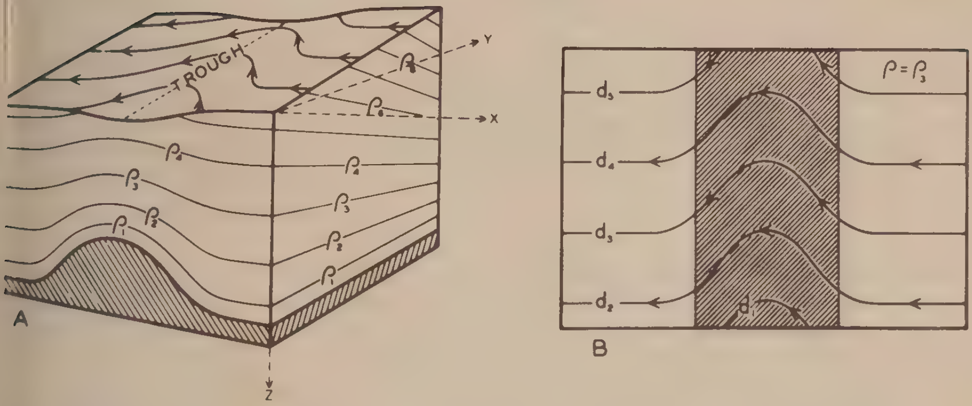
$$\frac{\partial p}{\partial x}\frac{\partial \rho}{\partial y}-\frac{\partial p}{\partial y}\frac{\partial \rho}{\partial x}=0$$

The latter equation states that the directions of the horizontal pressure gradients and density gradients coincide and that therefore the isobars and isopycnals in a horizontal surface must be of similar form. If this condition shall be fulfilled at all levels, it follows from the hydrostatic equation that the isobars and isopycnals must at all levels be of similar form. This is the "law of the parallel solenoids" by Helland-Hansen and Ekman[1] which has been found to be approximately fulfilled in the sea.

In the sea the great differences in density in a horizontal direction and, consequently, large inclinations of the isopycnic surfaces occur in the upper layers only. It is therefore often assumed that strong ocean currents are found in the upper layers only, and that the motion of the deep water is very slow, meaning that at great depths isobaric surfaces are nearly horizontal. On this assumption and by means of the above relations, one can find the qualitative effect on ocean currents of submarine ridges or peaks which rise from the ocean bottom.

EFFECTS OF SUBMARINE RIDGES AND PEAKS

Consider a current which in the Northern Hemisphere flows from right to left and approaches a submarine ridge. At some distance from the ridge the lowest isobaric and isopycnic surfaces are horizontal, as indicated in the right-hand cross section in the perspective diagram in Fig. 2A. With increasing distance from the bottom the isopycnals slope down to the right of an observer looking in the direction of flow, and the isobars slope down to the left. The upper surface of the block diagram is supposed to represent the free sea surface which is taken to be an isobaric surface, the downward slope of which is indicated. On approaching the ridge the isopycnic surfaces must rise, consequently the isobaric surfaces must sink, and the current becomes deflected to the right. After having passed the ridge the isopycnic surfaces sink, the isobaric surfaces rise, and the current is



ig. 2. A. Perspective diagram showing the influence of a submarine ridge on the distribution of density as represented by isopycnic surfaces and on the currents. B. Topography of an isopycnic surface = ρ_3) shown by lines of equal depth below sea level.

lected to the left. As a result of these modifications, free surface which at some distance from the ridge ped from right to left only must show a trough over the marine ridge and, correspondingly, the current shows a d to the right, the maximum deflection from the straight rse occurring over the center of the ridge (see Fig. . These modifications are all shown in the block diaam in Fig. 2A. The same diagram is applicable to the thern Hemisphere if the arrows are reversed. There current is deflected to the left from its straight rse.

The field of mass is shown in Fig. 2A by isopycnals two vertical planes. It could also have been repreted by isopycnals in horizontal surfaces or by the ography of isopycnic surfaces. In the latter cases isopycnals or the contours are horizontal streamnes. Because an isopycnic surface slopes at right gles to the current but is lifted when the current sses a submarine ridge, the topography of the surface ws a sloping ridge above the submarine ridge, as indied in Fig. 2B.

The disturbance of the fields caused by the ridge t be equally developed at all levels if an approximately ady state exists, because otherwise the law of the allel solenoids would not be fulfilled. An effect of bottom topography may therefore be observed in the face currents if the entire current is sufficiently p. A ridge which is two or three thousand meters

low the surface may lead to large deflections of the cur-
nts at all levels above the ridge.

Similar reasoning is applicable if a submarine peak
ses in the path of the current. The isopycnic surfaces
ove a peak must be dome-shaped and, correspondingly, a
unter-clockwise whirl must be present above the peak in
e Northern Hemisphere and a clockwise whirl in the
uthern Hemisphere.

The above reasoning, as already stated, is only quali-
tive. If the complete hydrodynamic equations are used,
d if boundary conditions and the continuity equation are
ken into account, it is found that the described fields
nnot be stationary. The velocity field, which has not
en discussed, can, for instance, be stationary only if
e current is directed east-west. This statement is
sily verified by means of Eqs. (1) and (2). It seems
obable, however, that the major modifications will be
presented, but that superimposed upon these major
difications will be found irregular eddies which may
avel with the general current. This conclusion can be
sted by examining the distribution of density where a
re or less well-defined current crosses a submarine
dge or passes a peak.

In oceanography it is customary to describe the dis-
ibution of density by means of the quantity σ_t which is
fined by $\sigma_t = (\rho_{s,t} - 1)\,10^3$. The density is here written
$\rho_{s,t}$ in order to indicate that one considers the den-
ty at the observed salinity and temperature, but at a
essure of one atmosphere. It can be shown that the
stribution of density can be represented with suffi-
ent accuracy by σ_t-surfaces and that the deformations
these surfaces are similar to those of the actual
opycnic surfaces. Therefore, within a current in the
rthern Hemisphere, the σ_t-surfaces slope down to the
ght of an observer looking in the direction of flow
d must be expected to show a ridge over a submarine
dge and a dome over a submarine peak. In the Southern
misphere they slope down to the left of an observer
oking in the direction of a current, but similar
dges and domes must be present. The effect of the
ttom topography can conveniently be examined either
constructing the topography of a selected σ_t-surface
d comparing this to the topography of the bottom or
plotting σ_t-curves in a vertical profile and comparing
e course of these curves with the corresponding pro-
le of the bottom. Examples of both methods will be
ven.

EXAMPLES

In Fig. 3 is shown the topography of the surface $\sigma_t = 27.7$ $\rho_{s,t} = 1.02770$) in the region from Drake Passage between uth America and the Antarctic Continent to longitude 18°W the South Atlantic Ocean. Arrow heads are entered on the ntour lines in order to indicate the direction of the

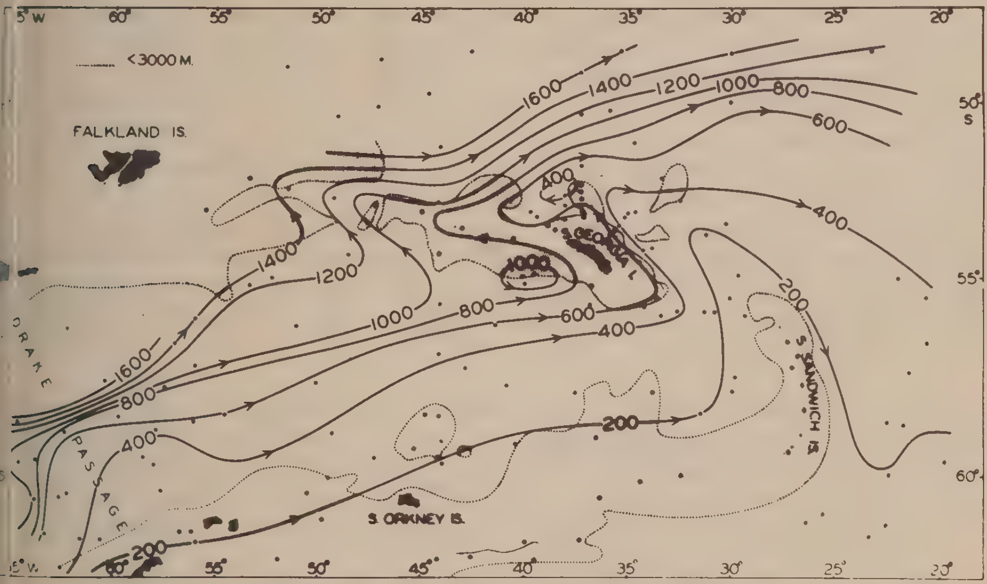


Fig. 3. Topography of the surface $\sigma_t = 27.7$ in the region between Drake Passage and longitude 20°W in the South Atlantic Ocean. Lines of equal depths are drawn at intervals of 200 meters, direction of flow is indicated by arrows, areas of depths less than 3000 meters are shaded.

rrents. The Antarctic Circumpolar Current flows through ake Passage from west to east and, correspondingly, the -surface slopes down from south to north from a depth of 0 meters on the right-hand side of the current to a pth of 1600 meters on the left-hand side. Above the bmarine ridge between South Georgia and the Falkland lands the dominating influence of the bottom topography evident because above this ridge the σ_t-surface shows corresponding ridge, the axis of which coincides with e axis of the submarine topographic feature. Correspondingly, the current is deflected to the left. The dge on which the South Sandwich Islands lie exercises similar influence.

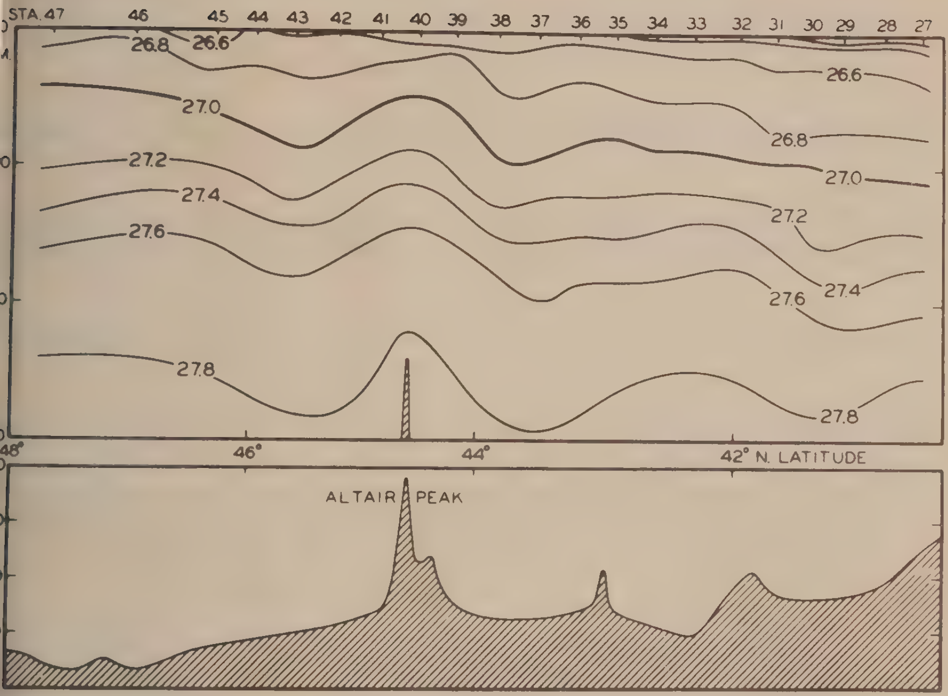
The chart is based on the numerous observations of e "Discovery" Expeditions and on the "Meteor" stations

in the area under consideration, most of which were occupied in March and April, the others in October and November. The localities of the stations used are indicated by dots. When drawing the contours of the σ_t-surface a smoothing of the direct observed values was made by hand, in order to bring out the major features. Such a smoothing is justified in view of the facts that the observations were made in different years and seasons, that a steady flow is not present and that local disturbances may be expected, particularly over the submarine ridge and on its leeward side. Some disturbances, however, appear to be localized. At the north end of South Georgia a counter-clockwise whirl is found in front of the islands and a clockwise whirl behind the islands. The latter is particularly well established by the available data and may be compared to the wake behind a cylinder. Thus, the large-scale pattern of flow has features in common with those observed on a very small scale in laboratories. It is even possible that more detailed observations would reveal a series of vortices behind the islands comparable to the von Kármán vortex trail.

The topography of the sea surface and the topography of isobaric surfaces at the approximate depths of 300 and 600 meters have been examined by Clowes[2] and Deacon[3], whose charts show that in the isobaric surfaces troughs correspond to the ridges of the σ_t-surface = 27.7.

Fig. 4 shows σ_t-curves in a vertical section to the north-northwest and north of the Azores as far as latitude 48°N and the bottom profile on a smaller vertical scale. The figure is based on observations of the International Gulf Stream Expedition in 1938.[4] The section crosses the branch of the Gulf Stream system, the North Atlantic Current, which flows from west to east, i.e. away from the reader. Correspondingly, the σ_t-curves slope down from north to south, the curve $\sigma_t = 27.0$ sinking about 350 meters. The similarity of the σ_t-curves indicates that the law of the parallel solenoids is approximately fulfilled except near the surface where the density of the water is influenced by processes of radiation and by convection, evaporation, and precipitation.

It was planned to carry out the investigations on the western side of the Mid-Atlantic Ridge where the depth to the bottom was supposed to be uniformly great, but sonic soundings led to the discovery of an isolated peak, the Altair Peak, which rises steeply from a depth of about 3500 meters to a depth of 973 meters. The sections upon which Fig. 4 is based did not pass over the top of the peak but a few miles to the west of the top, where the smallest depth was about 1500 meters.



ig. 4. Vertical sections showing σ_t-lines (above)
nd bottom profile (below) at right angles to the
orth Atlantic Current to the north of the Azores.

The effect of this peak on the field of mass is plainly
n. Over the peak the σ_t-surfaces rise; they are proba-
dome-shaped, and the accompanying disturbance in the
ocity field has probably the character of a counter-
kwise whirl. These conclusions have been confirmed
Wüst's[5] analysis of the currents at depths of 25 to
meters, based on the distribution of temperature and
inity.

Other examples could be added. Thus, Schumacher[6]
ts out that according to ships' observations the west-
ing Atlantic North-Equatorial Current bends to the
h when approaching the Mid-Atlantic Ridge and to the
h after having crossed the Ridge. The maximum de-
tion to the north occurs directly above the ridge
h lies more than 2000 meters below the surface.
ilarly, around the Antarctic Continent a series of
ections of the currents is found corresponding to
e shown in Fig. 3, but not so conspicuous. It ap-
s, therefore, that the observed deflections which
related to bottom topography are not caused by bottom
tion, as assumed by Ekman, but are caused by the

ications of the density distribution which have here
explained qualitatively.

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Contribution No. 135

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IS EVOLUTION INSCRUTABLE?

THE undeniable importance of Professor Goldschmidt's recent volume on evolution,[1] and the weight which its author's name justly carries, make it doubly needful that certain of its implications be fully recognized. Dobzhansky's assertion[2] that the acceptance of Goldschmidt's central theory demands a "belief in miracles" seems to me to be literally true, though the statement deserves some amplification.

The difficulties which beset the Darwinian theory of evolution through the natural selection of small variations were recognized by many of Darwin's contemporaries, and were discussed at great length by Darwin himself. Alternative theories of "saltation" or progress through large, discontinuous "jumps" were proposed by contemporary critics, notably by St. George Mivart.[3] Indeed, the rudiments of this idea long antedated Darwin, as witness Geoffroy St. Hilaire.

Mivart's evolutionism, as is well known, was strongly tinged with theology. The continuous intervention of the Creator in the evolutionary drama was fundamental in his world outlook. There was nothing disturbing to him in the notion that complex, adaptive structures could arise abruptly, since all this happened under divine guidance. The "innate tendency" to vary he conceived to be "an harmonious one, calculated to simultaneously adjust the various parts of the organism to their new relations."

It is needless to say that Professor Goldschmidt entertains no such theological interpretation of natural phenomena. Nor can we suspect him of sympathy with "vitalism," "teleology," "innate tendencies" or other forms of biological mysticism. Indeed, Gold-

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[1] "The Material Basis of Evolution." Yale University Press, 1940.

[2] SCIENCE, October 18, 1940.

[3] "The Genesis of Species." Macmillan and Company, 1871.

Contributions from the Scripps
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schmidt's position would perhaps be more understandable if he did cherish such views. For he contends that "macroevolution" (*i.e., real* evolution) comes to pass through single, abrupt genetic changes ("macromutations"), capable of bringing about phenotypic alterations of specific, generic or even much greater magnitude. The role of selection is limited to the "immediate acceptance or rejection" of the finished product. Even St. Hilaire's suggested origin of the first bird from a reptile's egg, as repeated by a recent paleontologist, is cited by Goldschmidt with seeming approval.

We should surely need the guiding hand of an entelechy here, if not the direct intervention of the Creator himself. That a single, small, genetic change can produce varied and far-reaching somatic changes no one is better qualified to tell us than Professor Goldschmidt. That somatic changes produced in this way have any necessary tendency to be functionally integrated he has not, however, shown to be probable. Yet the most casual examination of any complex organ shows that it is made up of innumerable interrelated parts, harmoniously adjusted to one another. Consider the structure of even a bird's feather! Only the wave of a magician's wand could have transformed the scales of a reptile forthright into the plumage of a bird.

The trouble here is not so much that we are concerned with very great changes, structural and functional, but that these changes must involve the harmonious modification of parts which are to a large extent independent of one another genetically. Goldschmidt's assurance that "a simple shift in the velocity of one of the integrating processes relative to the others will account for the primary change with all the later unavoidable consequences during subsequent development" may suggest a partial solution of some of the difficulties. It can hardly apply, however, to cases involving the simultaneous though not necessarily parallel, modification of different organ-systems, and particularly to the appearance of fundamentally new structures in some of these. Mivart realized the difficulty of accounting for such functional integration in a theory of evolution by "jumps" and called in a supernatural agent to help him out.

Recent biology has sometimes shown itself so unsympathetic toward the conception of "adaptation" that it has even tended to overlook the facts to which this term is applied. Darwin was largely concerned with the endeavor to explain these facts. We can not, indeed, take them for granted, unless we are prepared to abandon the search for a naturalistic explanation.

It is significant that Goldschmidt's most voluminous line of evidence for the production of major bodily changes through single genetic steps is drawn from the field of rudimentation. Under this head, he has assembled a mass of highly interesting facts. It has long been known that even a single gene mutation may result in the degradation or loss of such important structures as an insect's wings or eyes. It is, however, easy to misinterpret such facts. May I repeat a doubtless unoriginal utterance of my own on this subject: "That a single and extremely simple alteration may effect a radical change in an object, even to its complete annihilation, proves nothing as to the degree of complexity of the object itself or of the processes necessary to bring it into existence."[4]

If Professor Goldschmidt can point to any one case in which a new, complex, adaptive structure has arisen through a single genetic change, and if this same genetic change is shown to have involved the necessary correlative changes in many other parts of the body, he will have gone a long way toward proving his main contention. But he will, at the same time, have left naturalistic biology in a most embarrassing position.

F. B. SUMNER
SCRIPPS INSTITUTION OF OCEANOGRAPHY

[4] *American Naturalist,* March–April, 1934.

Contribution No. 137

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PIGMENTS FROM MARINE MUDS*

BY DENIS L. FOX AND LLOYD J. ANDERSON

SCRIPPS INSTITUTION OF OCEANOGRAPHY

Communicated June 2, 1941

Earlier investigations in this laboratory[1] revealed the presence of carotenoids, along with greenish pigments presumably representing the breakdown of chlorophylls, in muds from the ocean floor.

An opportunity for studying such pigments more extensively and in greater quantities has been provided recently through the kindness of Dr. R. R. Revelle and his associates at the Scripps Institution, whose oceanographic and geological researches in the Gulf of California were supported by a grant from the Geological Society of America.

The mud core sections placed at our disposal were taken from the sea floor near the middle of the Gulf, at latitudes between 27° 17.2′ and 27° 53.6′, longitudes between 110° 41.5′ and 111° 7.9′, at depths ranging between 201 and 1750 meters below the water-surface and from sediment layers between 8 inches and 17 feet beneath the surface of the bottom. The muds were free from oxygen; indeed many of them evolved either H_2S or an inflammable gas (CH_4 and H_2) when first brought up. Samples were stored in sealed tins at low temperatures until the time of analysis. Pigments were extracted from mud samples by exhaustive treatment with acetone, transferred to petroleum ether and resolved into two gross primary fractions, i.e., preferentially soluble in either the latter solvent or 90 per cent methanol. Chromatographic adsorption on Tswett columns of $CaCO_3$ removed all of the several greenish pigments from the methanol-free epiphasic petroleum ether solution, while yellow or orange pigments of the carotene class were similarly separated on layers of $Ca(OH)_2$ below. Hypophasic fractions (in 90 per cent methanol) were generally quite free of green pigments and contained only oxygenated carotenoids of the xanthophyll group. After transference to pure petroleum ether or benzene, they were separable into chromatographic fractions on $CaCO_3$ columns.

Studies of differences in solubility, chromatographic adsorption, behavior toward treatment with alcoholic alkali, and types of absorption spectra have revealed the presence of a series of greenish pigments (presumably derived from chlorophyll breakdown) and numerous epiphasic and hypophasic carotenoids.

Green Pigments.—Three principal fractions were separated, one soluble in petroleum ether and resolvable into two chromatographic zones, another insoluble in petroleum ether but soluble in acetone and a third insoluble in petroleum ether with or without acetone, but soluble in aqueous acetone. Each pigment showed from three to four absorption bands in the visible spectrum, occupying positions from the blue-green (507 mμ) to the red (683 mμ). Treatment of any of the pigments with alcoholic KOH caused some breakdown, resulting in colored bodies with simpler spectra, but always showing, like the parent substances, a prominent absorption maximum in the red and general increasing absorption in the violet and shorter wave-length regions. A prominent pigment occurring in the petroleum ether fraction of all extracts showed an absorption spectrum very like that recorded by Rothemund[2] for hemp-speed protochlorophyll, its maxima in ethyl ether being at 507, 537, 611 and 667 mμ, and in chloroform at 510, 546, 630 6 and 682 mμ. Incineration yielded no ash.

Chlorophylls themselves were never encountered, but the other green compounds were found in quantity at all depths studied. Assuming that these green pigments are decomposition products of chlorophylls from diatoms and other marine algae, the recovery of striking quantities of a pigment closely resembling protochlorophyll from ancient, strongly reducing marine deposits reëmphasizes questions pondered by plant biochemists regarding biochemical relationships between protochlorophyll and chlorophyll.

Carotenoids.—Most of these pigments remained in the epiphase. The additional facts that they remained epiphasic to 90 or even 95 per cent methanol after treatment with hot alcoholic KOH and that they were unadsorbed by $CaCO_3$ placed them in the carotene class. A predominant pigment of this group showed absorption maxima agreeing closely with those of β-carotene. α-Carotene was represented in smaller amounts, while other pigments were encountered which exhibited two or three absorption bands not listed in the literature, but not very unlike rhodopurpurin extracted from the pigmented bacterium *Rhodovibrio.* A pigment with absorption maxima close to those of torulene from the red yeast, *Torula rubra,* was found in several samples. On one occasion, hydrolysis of the torulene zone from the chromatogram yielded an acidic carotenoid with a single absorption maximum at about 500 mμ in pyridine. These properties, with its deep rose color in CS_2, likened it to astacene, encountered in certain invertebrates.

The hypophasic fractions included pigments showing absorption maxima agreeing closely with those of fucoxanthin (found in many marine algae), lutein and zeaxanthin. There were numerous xanthophylls with unfamiliar absorption spectra. No acidic carotenoids were found in any of the hypophasic fractions.

While quantitative estimations of pigments have not yet been correlated with depth of mud, such work is anticipated. However an account of a preliminary analysis made of one sample will be of interest. One gulf-bottom core taken at lat. 27° 41′, long. 110° 55′ at a depth of 666 m. was 17 feet in length and yielded an inflammable gas from its deeper layers.

Two hundred fifty grams of mud, taken from the 15 to 16.3 foot level yielded 5.22 mg. of epiphasic carotenoids (in equivalents of β-carotene with whose absorption spectrum that of the mixed pigments was very similar) and 2.33 mg. of hypophasic carotenoids (in equivalents of lutein, whose absorption spectrum was similar) giving a figure of about 3 mg. carotenoids per 100 grams wet mud, or some 6 mg. per cent on a dry basis.

Such quantities of natural pigments, chemically unstable under ordinary conditions, would seem to be rather remarkable when one considers the probable age of this deep layer of mud in the gulf, estimated by Dr. Revelle as being some 6000 to 7000 years (personal communication). The absence of living photosynthetic plants and the extreme paucity of active forms of other microörganisms would suggest that we are dealing here with fragmentary biochemical chapters of past ages. The pigmentary record in buried marine muds is probably altered but little with the passage of time, due to stable conditions of darkness, low temperatures, little if any biological activity and especially the absence of oxygen.

Gulf muds yielded pigmentary compounds in greater quantity than did bottom-samples examined from the open ocean. No obvious differences were noted in quantity of pigment extractable relative to depth below the mud surface. It is expected that quantitative data will be available later.

Other Pigments.—While no such substances as the one about to be described were found in any of the samples of gulf mud examined, one non-carotenoid fluorescent pigment attracting special interest occurred in a mud core taken from the open sea (about lat. 32° 30′, long. 117° 30′) at a depth of some 1300 meters. Samples from the first six inches and from the 6 and 7 foot mud-depth yielded green pigments and carotenoids, but a section from the 40 to 46 inch level yielded, along with the usual green pigment (absorption maximum 669 mμ in petroleum ether from all four core-sections examined), no carotenoids, but instead a deep brown-yellow pigment, showing pronounced green fluorescence in petroleum ether solution.

A pigment obtained from a sample of heavy crude petroleum from Kern County† showed striking similarities to the one just mentioned. Each pigment was dark, amorphous and tarry, preferentially soluble in petroleum ether over 90 per cent methanol, sparingly soluble in pure methanol, showed blue-green fluorescence in petroleum ether or chloroform, and passed through $CaCO_3$ in benzene solution, showing a diffuse brown zone at the upper end of the $Ca(OH)_2$ column. Further, a series of three chromatograms, involving (1) the mud pigment, (2) the oil pigment and (3) a mixture of these two, gave a similar, single zone of brown sorbed material in each tube (the so-called "mixed chromatogram" used in testing suspected identical compounds). Finally, each pigment gave the same absorption maxima, at 575 mμ and 553 to 554 mμ.

These comparative observations and tests indicate the identity or close chemical relationship between a pigment from marine mud and one separated from crude petroleum. Dr. Revelle's estimate of the age of the deposit of mud at the depth from which the pigment was obtained is about 4000 years (personal communication).

Résumé.—The demonstration of numerous chlorophyll derivatives and carotenoids in ancient marine deposits is thought-provoking. Chlorophylls are known to undergo advanced biochemical changes in animal organisms, while carotenoids found in feces may retain their complete integrity. The absence of chlorophylls themselves in the presence of a suspected protochlorophyll and other simpler degradation products leads to a consideration of possible biochemical changes wrought by non-chlorophyllous microorganisms, and emphasizes the questions regarding interrelationships between chlorophylls and protochlorophyll in green plants.[2]

The encountering of relatively rich deposits of numerous carotenoids also bears on the question of metabolic activities in marine muds. Does the preponderance of carotene-like pigments over xanthophylls in gulf muds actually indicate an excess of fungal and bacterial over algal remains, or have isomerization and other chemical changes taken place, with or without biological intervention, to alter so extensively the situation encountered in marine algae?

The question of synthesis of carotenoids by bacteria and fungi isolated from marine muds is being investigated, and problems involving possible changes in chlorophyll and certain carotenoids by such organisms are being undertaken.

The encountering of a fluorescent, non-carotenoid pigment in both a sample of crude petroleum and a marine mud core (accompanied in the latter by a green pigment, supposedly resulting from chlorophyll degradation) lays emphasis upon the importance of continuing investigations on the biogenic origins of petroleum.

Acknowledgments.—Grateful thanks are expressed to Dr. Roger Revelle and his associates of this Institution for the mud samples and for useful information regarding them; to Mr. R. A. Halloran of the Standard Oil Company of California for the crude petroleum sample and information pertaining to it, and to several members of the Works Progress Administration Project (No. 65-1-07-2317) for valuable routine assistance rendered in the laboratory and in the preparation of the manuscript.

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* Contributions from the Scripps Institution of Oceanography, New Series No. 137

† This sample, kindly furnished by Mr. R. A. Halloran, Manager of the Research and Development Department of the Standard Oil Company of California, is designated by Mr. Halloran as originating in marine formations of upper Miocene or lower Pliocene age (Sample number 25292-R).

[1] Fox, D. L., *Proc. Nat. Acad. Sci.*, **23**, 295–301 (1937).

[2] Rothemund, P., *Cold Spring Harbor Monogr. Quant. Biol.*, **3**, 71–79 (1935).

Contribution No. 138

Reprinted from SCIENCE, June 27, 1941, Vol. 93,
No. 2426, pages 617–618.

RATE OF SURFACE RETREAT OF SEA CLIFFS BASED ON DATED INSCRIPTIONS[1]

SINCE the time of cave man, people have responded more or less to an urge to draw pictures or cut inscriptions on walls. Although this habit is often objectionable, some use can be made of it geologically in estimating the rate of rock surface weathering and erosion.

Near La Jolla, California, the sea cliffs are largely composed of Cretaceous and Eocene rock. Much of this material is sandstone, consisting of medium to coarse-grained quartz and feldspar, moderately to firmly cemented by $CaCO_3$ when fresh, but friable when weathered. Along four miles of this coast a great number of roughly carved names or initials were found on the sandstone during August, 1940. Even though fewer than 10 per cent. were accompanied by the date on which the carving was made, a total of 163 dated inscriptions were located. Since beach vacationists have come to La Jolla for many years, an interesting frequency curve for such dated signatures can be made (Fig. 1). Enough data are available so that the effect of a few deeply cut carvings, of falsification and of errors in reading partly obliterated dates is minimized.

Most of the freshly cut letters are a sixteenth to a quarter of an inch deep. Within a few months after being cut, definite signs of solution and wearing away of the edges appear, until in about a year there remain no sharp edges whatever. In two or three years the lines usually become only broad shallow grooves in the rock surface and in four or five years they are partly obliterated and can be read only with difficulty. In several instances, where the grooves for old carvings had been almost completely destroyed, the lines are partly shown by rows of barnacles which had lived in the grooves probably because a water film was held there longer than on the flat rock surface.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 138.

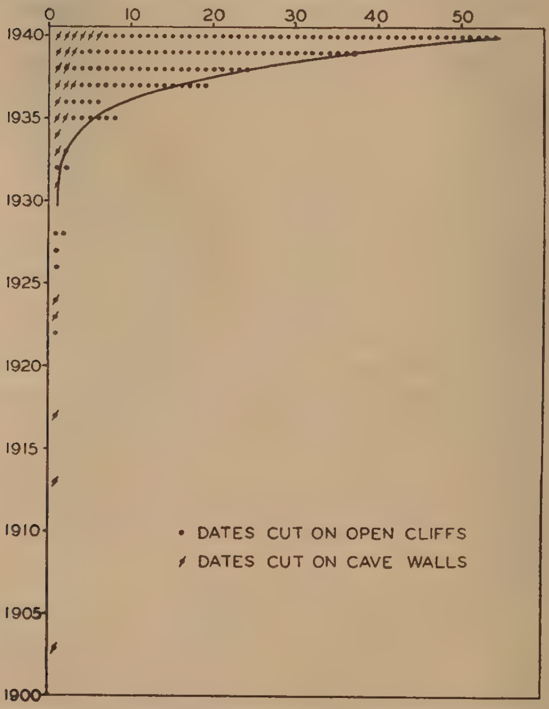

Fig. 1. Graph showing number of dated inscriptions found cut in sandstone sea cliffs near La Jolla, California.

Destruction of the carvings seems to take place largely through solution of the $CaCO_3$ cement in the rock. The loosened grains may be detached by the formation of salt crystals developed by the evaporation of spray or at some localities they may be carried away through direct erosion by sediment-laden waves. Interestingly enough, the dates which have remained legible for the longest time are those cut on the walls of caves or narrow inlets where the rock rarely becomes completely dry.

On the basis of carvings made in 1940, the depth of the average inscription was estimated to be one eighth inch. If six years are required to obliterate a carving (Fig. 1), a period of about 600 years would be necessary for surface weathering and erosion alone to cause the sandstone cliffs to retreat one foot. This figure probably represents a maximum rate for the sandstone, however, since obliteration takes place not only by retreat of the entire cliff front, but also by mere broadening of the letters into a wide hollow. A much higher rate of retreat exists for local cliffs of relatively unconsolidated terrace material near La Jolla. These are cut back by waves and rain wash so rapidly that only one or two 1940 carvings were found. An even lower rate for limestone (one foot in 6,000 years) was obtained by Goodchild[2] through the investigation of gravestones. The slowness of the retreat suggests that other processes such as undercutting by waves is primarily responsible for the cutting back of the cliffs at La Jolla. At the rate of retreat of one foot in 600 years, a cliff twenty feet high would contribute to the beach about 3.3 cubic feet of sand annually for each one hundred feet of its length. Although the method is subject to errors, it may be an approach for determining relative rates of surface weathering and erosion in other areas.

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[2] J. G. Goodchild, *Geol. Mag.*, 12: 326, 1875; *Geol. Mag.*, 27: 463–466, 1890.

Contribution No. 139

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 2, PP. 92–93, FIG. 1, AUGUST, 1941

TRANSPORTATION OF ROCK PARTICLES BY SEA-MAMMALS*

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ABSTRACT

Gastroliths, sometimes in large quantities, have been found in the stomachs of many sea-mammals. Although the animals are not of great importance as agents of transportation, they provide an interesting demonstrated means of pebble rafting.

In the geological literature, there are a few references regarding the efficacy of sea mammals in distributing pebbles carried as stomach stones. The source material quoted, however, has been no more recent than the reports of the Challenger Expedition (Murray and Renard 1891), although later data are available.

Stones have been found in the stomachs of the California sea lion, the Steller's sea lion, the sea elephant, the fur seal, the Peruvian seal, the harbor seal, and the Walrus (Scammon, 1874; Turner, 1887; Jordan, 1898; Johansen, 1912; Howell, 1930; Schroeder and Wegeforth, 1935; C. R. Schroeder, C. M. Hermann, G. E. MacGinitie, personal communications). Single rocks weighing as much as five pounds and aggregates of 25 pounds are mentioned. Apparently none of the pebbles were carried long enough to become highly polished like the gastroliths of dinosaurs (Wieland, 1907).

The writer has examined the stomachs of 11 dead sea lions which had drifted up on beaches near La Jolla, California. Although most of these stomachs were completely empty, one contained a single flat pebble of sandstone, and another had the pebbles shown in figure 1. Twenty-three of these rocks are wave-rounded Black Mountain metavolcanics, the other four are fragments of shale probably of Eocene or Cretaceous age. All of these types of rock are available on beaches near La Jolla. Because of the angularity and fragileness of the shale, it seems likely that the stones had not been carried very long by the sea lion, although some of the metamorphics seem to be very slightly polished.

Formerly the stones were thought to serve as a ballast to aid in diving (Murray and Renard, 1891). Later it was suggested that they might serve as a sort of "gastric chewing gum" to prevent atrophy of the male's stomach during the long period of fasting in the mating season (Howell, 1930). A function of crushing worms which frequently infest stomachs or of rubbing ulcers has also been proposed. More recent work, however, seems to check Turner's conclusion (1887) that the pebbles are used to triturate food (Schroeder and Wegeforth, 1935; C. M. Hermann personal communication). Schroeder has also noted that large numbers of pebbles are removed from the floor of zoo tanks by sea lions and seals soon after feeding, and a few hours later they reappear in their former abundance on the tank floor, apparently having been regurgitated after the food had been digested.

Although it is certain that some sea mammals are a factor in the distribution of pebbles on the sea floor, they cannot be quantitatively important as geological agents. On the other hand, it should be borne in mind that the presence of infrequent pebbles in fine-grained sediments may sometimes be due to the activity of sea mammals as well as to other forms of rafting.

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* Contributions from the Scripps Institution of Oceanography, New Series, No. 139.

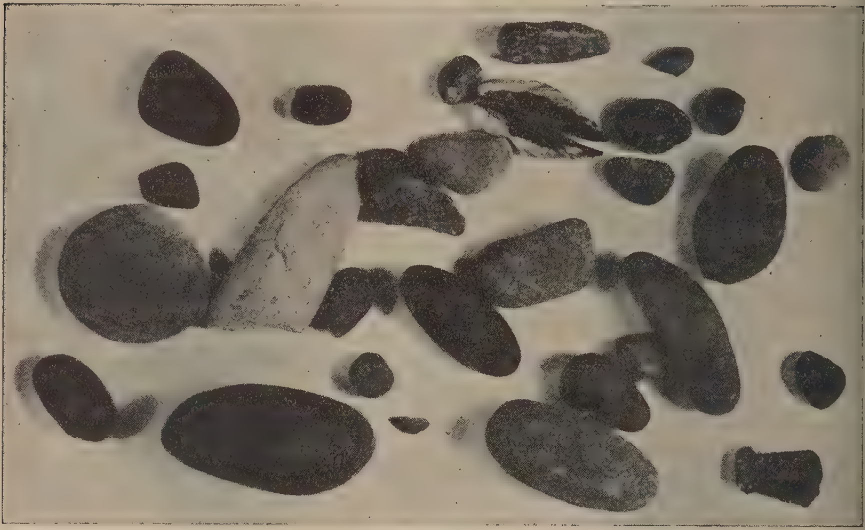

Fig. 1.—Pebbles removed from stomach of female sea lion at La Jolla, California. Rounded dark pebbles are Triassic Black Mountain meta-volcanics; lighter flat fragments are Eocene or Cretaceous shale. Note the single mussel shell. (×½)

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Contribution No. 140

DEPTH RELATIONSHIPS OF PLANKTON DIATOMS IN SEA WATER*

By

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For more than twenty years I have been directly interested in the space relationships of marine plankton organisms. Not least among the unsolved problems of these relationships is that of the maintenance of residence at appropriate depths by microscopic creatures, e. g., the plankton diatoms. Even the questions concerning the fate of the dead bodies, empty frustules, or other remains of these tiny plants have considerable importance not only for the marine biologist but also for the marine hydrologist, or physicist, or chemist. Such problems are difficult enough if presented in the simplest form for a particular kind of particle of designated shape, density, dimensional limits, frictional characteristics, solubility, etc. They are far more difficult in Nature because of the endless complications and modifications introduced by biological influences of many kinds.

Still, I believe that there exist certain major tendencies of behavior of microscopic particles in respect to maintenance of level or change of levels in natural waters which might be worked out if a well organized program of investigations were carried over a period of time and a wide extent of observable conditions. However, I do not believe that the rate of settling of marine plankton diatoms, or of their frustules (the kinds of small particles most familiar to me) can ever be expressed dependably by a mathematical formula because, at any given point in the sea, sinking may occur according to formula today and not tomorrow, the difference being due to influences added, subtracted, or modified in ways not open to prediction.

While a study of marine deposits shows that plankton diatoms are represented in them, this representation is much less than might be expected from our knowledge of excessive abundances in many seas. The reasons for this condition are probably to be found mainly in the characteristics fitting the plankton forms for a suspended existence and in the influences contributing to their suspension. Consequently, there are interesting relationships between the problems of suspension

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and of deposition as well as between those of suspension and maintenance of life.

There are recorded nearly two hundred species of marine diatoms which seem to spend most of their active existences adrift. For all such it appears that suspension must be an advantage and that they must possess some means of regulating it within necessary limits. For them the primary need is to keep suspended at the levels which are favorable for their growth and development. Confronted with the endless vagaries of waves, currents and other disturbances, this often proves to be impossible. On the other hand, the vast numbers in which these tiny plants appear from time to time in many parts of all oceans show that they have some means for keeping contact with tolerable if not with favorable conditions. Needless to say, these powers of holding an acceptable level add indefinitely to the difficulty of measuring or of describing their powers of suspension and of distinguishing between physical and biological causes of the phenomena of suspension or of deposition in any particular case.

In the discussion of ability to keep adrift considerable stress is rightly given to the production of gases and oils by the living substance. Since the microscopic plant has nearly the same specific gravity as ordinary sea water, it seems to be certain that a slight change in relative volume of either gas or oil would suffice to make the diatom either lighter or heavier, and so capable of shifting position slightly in either the downward or upward direction. Since it is improbable that for any individual diatom this power of adjustment would be worth much in relation to change in level, it seems probable that its value would lie in approximate maintenance at a tolerable or favorable level.

A less changeable feature in relation to suspension is that of structure of the frustules, the walls being thinner and lighter in all floating diatoms and showing highly modified protuberances in many forms. In the genus *Chaetoceros* these protuberances have the shape of delicate hairs many times longer than the main body and so presenting a relatively enormous expanse of surface to delay sinking. Some kinds of plankton diatoms get similar relative expanse of surface by merely lengthening the whole frustule into a thread, without much development of protuberances. Reduction in size of the body would have a similar effect but it is not clear that this would be likely to occur in a way to promote suspension at a favorable level.

Formation of mucous threads or films might be expected to give material aid to suspension by increase of friction over larger and moving surfaces, but since the diatoms of colder seas exhibit these developments more generally, it may be doubted that they have high value in that way. Still, it may be that they do and that they are more prominent in colder seas because of some coincidental condition.

In some species it seems probable that the extrusion of protoplasmic threads or streams aids in suspension, partly by exerting stream friction against the surrounding water and partly by increase of surface.

If suspension is really promoted by this means it can be more directly controlled than by any of the others mentioned. While, at first, it may seem improbable that the effect of protoplasmic extensions would be great enough to have appreciable effect on suspension, this improbability tends to disappear when one recalls that for the living diatom very little influence is needed to tip the balance of adjustments to favor suspension.

For the sake of clarity most of the foregoing discussion has been written as though the surroundings of marine plankton diatoms were fairly constant, as they are not even at a single chosen depth. Various features in the ordinary relationships of these surroundings may or may not aid in suspension at a favorable level. In many cases suspension is promoted by slight (unobservable) movements of small water masses either horizontal, vertical, or irregular. No trustworthy data exist from which to estimate the importance of this influence but that it must be considerable is indicated by the movements of diffusion and of mixing of minute and microscopic particles often observable in small masses of water and in air. On the other hand, it is still more certain that such movements may carry certain diatoms or certain populations to a lower or higher level or to some lateral point which is less favorable for suspension or maintenance.

Still more indefinite and elusive would be the effects of movements of vigorously swimming animals which must be directly disturbing to suspension of diatoms in any certain relation but which indirectly constitute aid to suspension by changing gaseous and organic content of the water and by promotion of vigor in all functions of the microscopic plant. This indirect effect might include removal of particular diatoms to levels extremely favorable, in which their increasing numbers and more vigorous growth would aid materially in securing suspension although the general alteration of relationships may have been considerable.

Ordinarily conditions of viscosity may be supposed to favor suspension of diatoms which have adjusted themselves to conditions at a particular depth in the sea, because viscosity is understood to increase with increase of pressure and with decrease of heat. But nearly all diatoms are active only at depths less than seventy meters, in all cases being confined to levels within reach of numerous causes of disturbance of water masses. For such reasons it appears that viscosity does not bear a constant relation to level and that it is subject to considerable variation at different points in any level, depending upon more or less immediate influences of wind, wave, and of bottom topography. The same is true of a number of other physical and chemical conditions which may have possibilities of influence on flotation.

In harmony with the foregoing suggestions it seems fair to assume that in ordinary conditions of all seas there is little tendency for plankton diatoms to settle to the bottom so long as they are in vigorous activity, either photosynthetic or assimilative. It is probable that those forms having heavier and smoother frustules are able to offset their greater tendency to sink by developing some peculiarity in this activity, for example, special formation of oils or frequent division to produce smaller cells.

At any rate, it seems to be certain that most of those tending to deposition are moribund, dead, or otherwise inactive. The more common forms of individual cells in plankton diatoms are smooth discoid, rough or spinose discoid, heavily setose discoid, cylindrical, spindle shaped, and filamentous. Many of them unite into chains so that they behave more or less like filaments. Even when the living matter has disappeared and only the bare frustules are left the chains are often prominent in a plankton catch and they are probably much more prominent in the undisturbed condition in the sea. This is especially true of smaller forms in the genus *Chaetoceros* which often appear in large numbers in the dead or cleaned (empty frustule) condition near the surface of the sea, indicating that sinking may be a long and highly variable process for many plankton diatoms.

Judging from the rate at which diatoms sink through a distance of several centimeters in a container in the laboratory one might conclude that they may sometimes settle from higher to lower levels in the sea at a rate of several meters per day, perhaps as many as twenty or thirty meters. However, no reliable data concerning the rate of sinking exist, not even as to the laboratory differences in rates shown in relation to the different species. Therefore, it seems highly probable that laboratory observations lack dependability as a basis for estimating or understanding the actual rates of sinking in the ocean, just as they do for so many other natural phenomena.

For one thing, the mere increase in viscosity as successive lower levels are reached in descending from the surface in many instances would be sufficient to materially change the rate of sinking, perhaps almost stopping descent below the hundred meter level for delicate frustules. This, together with slight movements of surrounding water particles might result in an empty frustule remaining afloat for so long that it would disintegrate or redissolve into a colloidal or other state in which its substance would remain suspended without ever being deposited. There seems to be a reasonable probability that this actually happens and that the lack of abundance of plankton forms in marine sediments is due to the ordinary tendency of sea water to reduce their delicate frustules to solution. That is to say, the problem of suspension or of sedimentation is intimately related to the problem of disintegration.

Lest it appear that I have merely succeeded in making the situation seem to be hopeless so far as the study of microscopic particles in the sea is concerned, let me say in conclusion that any addition to reliable information is helpful and important, no matter if it may fall short of full solution of the problems involved. Essential approximations to correct solutions may come later.

Contribution No. 141

THE WATER MASSES OFF THE WEST COAST OF NORTH AMERICA*

BY

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In reporting the results of the 1937 cruises of the "Bluefin" off southern California, Sverdrup and Fleming (in press) found that within the limited area which they investigated, two primary water masses were present, mixtures of which made up the water at depths between 200 meters and 400 meters in this region, and they developed a convenient method of using temperature-salinity relationships to study the processes of mixing. The present paper is an extension of the same method to all the waters which border on the west coast of North America from Alaska to Mexico.

A series of temperature-salinity curves from stations located at various points from the Gulf of Alaska to Central America show a regular transition in the character of the water masses from north to south and clearly indicate that the water along the entire coast is a mixture of two extreme water masses. The regions in which these masses lie have been called by Sverdrup, Johnson and Fleming (MS) the Subarctic North Pacific and the Equatorial Pacific regions, respectively. The former extends over the entire North Pacific at latitudes higher than about 43° N. and the latter covers a triangular area over the equatorial region of the Pacific, whose base lies in the western Pacific between about latitudes 20° N. and 15° S. and whose apex lies on the Equator at about longitude 130° E. The region of transition between the Subarctic and Equatorial waters includes that adjacent to the west coast of the United States and Mexico and extends to a distance of 400 to 600 miles or more from the coast. It was within this region of mixing that, in 1939, the "E. W. Scripps" occupied eighty hydrographic stations the locations of which are shown in Figure 15. The area indicated by the dashed line is that covered by the "Bluefin" in 1937. In Figure 16 is presented a series of T-S curves from the outermost stations (VIII 34–VIII 79) of the six station lines. Curves from four stations further to the north are included, those from "Catalyst" station C4843-12819 (48° 43′ N. 128° 19′ W.), "Carnegie"

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* Contributions from the Scripps Institution of Oceanography, New Series, No. 141.

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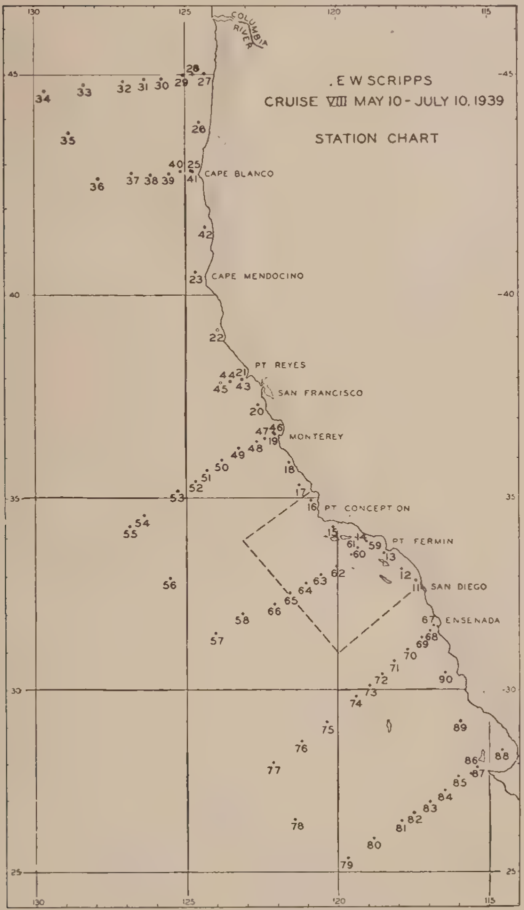
E W SCRIPPS
CRUISE VIII MAY 10 - JULY 10, 1939
STATION CHART
COLUMBIA RIVER
CAPE BLANCO
CAPE MENDOCINO
PT REYES
SAN FRANCISCO
MONTEREY
PT CONCEPTION
PT FERMIN
SAN DIEGO
ENSENADA
130
125
120
115
45
40
35
30
25

Figure 15. Station Chart, "E. W. Scripps" Cruise VIII.

stations 120 (47° 02′ N. 166° 20′ E.) and 124 (52° 19′ N. 162° 02′ W.) and "Bushnell" station *a*, 1934 (50° 30′ N., 175° 16.5′ W.), and from two stations to the south, "Bushnell" stations 299 and 307, 1939 (19° 02′ N., 86° 50′ W., and 22° 22.5′ N., 111° 25′ W.).

The curve from "Carnegie" station 124 in the eastern part of the Subarctic North Pacific region is similar to those from "Carnegie" station 120 and "Bushnell" station *a* in the western and central parts,

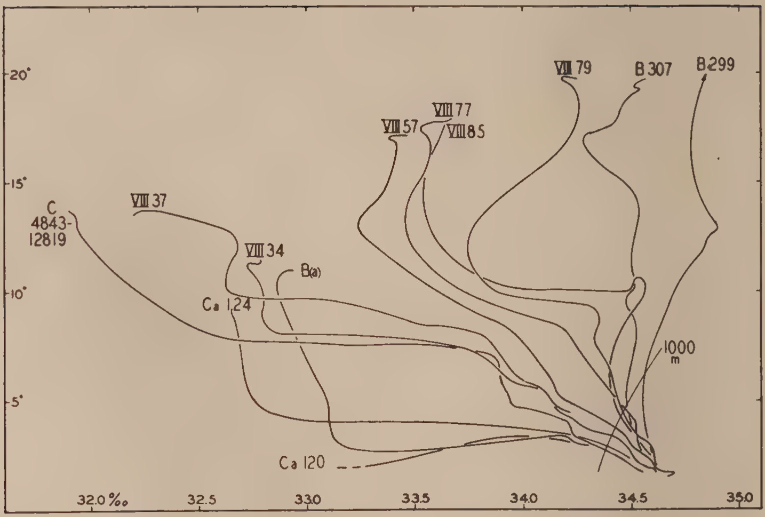

Figure 16. T-S Curves of Stations in the Eastern North Pacific from off the Aleutian Islands to Central America.

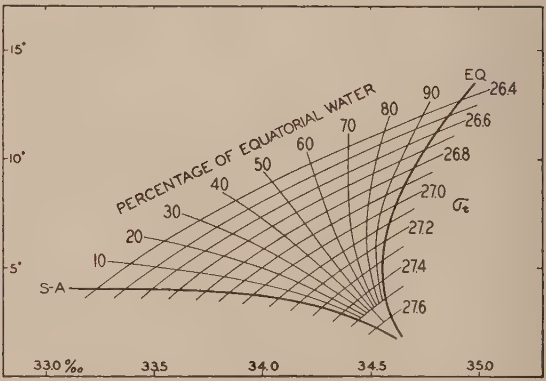

Figure 17. Graph showing T-S curves defining Subarctic North Pacific and Equatorial water, and curves for various percentages of Equatorial water assuming mixing along surfaces of equal σ_t.

and for our purpose is taken as defining the Subarctic water mass. The characteristic T-S curve defining the Equatorial water mass of the northeastern part of the Equatorial Pacific was obtained from "Bushnell" station 299. It is comparable to those from other "Bushnell," "Carnegie" and "Dana" stations in the region (Sverdrup, Johnson and Fleming, MS), and to the curve for Equatorial water derived by Fleming (1939). These characteristic T-S curves defining the Subarctic and Equatorial water masses are entered in Figure 17.

For further analysis it will be assumed that the observed distribution of temperature and salinity in the area of transition is maintained by horizontal flow and by lateral mixing of waters having the T-S relationships defined above, and that mixing takes place primarily along surfaces of equal σ_t. This latter assumption is equivalent to assuming nearly isentropic mixing. One cannot establish strictly isentropic surfaces in the ocean as Rossby (1939) has done for the atmosphere where, in dry air, they correspond to surfaces of equal potential temperature. Surfaces of equal density *in situ* do not fulfill the necessary conditions but those of equal σ_t closely approximate such isentropic surfaces. A body of water cannot be displaced even along a σ_t surface without somewhat altering the distribution of mass, nor will the mixing of two bodies of equal σ_t but of different temperatures and salinities result in a mass of the same σ_t. The departures are, however, small and may in a first approximation be disregarded.

On the assumption that water masses of intermediate character are formed by the mixing along σ_t surfaces of Subarctic and Equatorial waters, it is possible to prepare a diagram (Figure 17) from which the percentage of Equatorial water can be found for water of any observed temperature and salinity. In constructing this diagram, the σ_t lines were drawn between the two limiting T-S curves, SA and EQ, and were divided into the proportional parts from which smooth curves representing the several percentages of Equatorial water were drawn. It must be noted, however, that the determination of percentage composition by this means cannot be used for water above about 100 meters, since near the surface vertical mixing related to the effects of wind and local changes due to absorption of solar radiation, evaporation or precipitation are prominent and any mixing along σ_t surfaces will be more or less completely masked. This is especially true whenever the interval between stations in space or time is great. Below a depth of about 1000 meters the differences in the T-S relationships of the two extreme water masses are so small that application of the method is doubtful.

Figures 18 to 23 are vertical sections along the six station lines of Cruise VIII of the "E. W. Scripps" and were constructed from

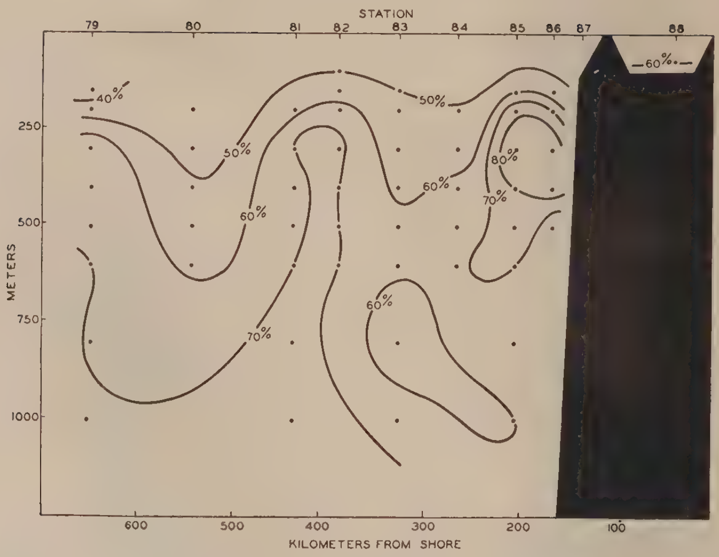

Figure 18. Section 6 off Cedros Island, Lower California, showing percentage of Equatorial water.

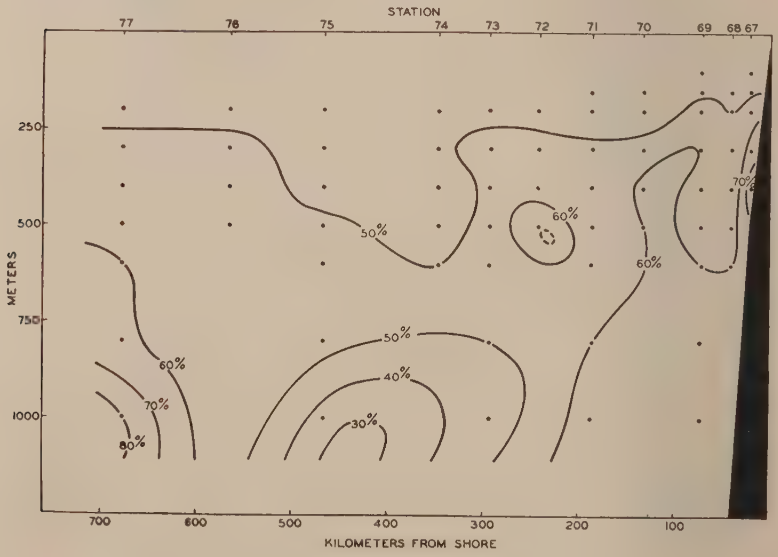

Figure 19. Section 5 off Ensenada, Lower California, showing percentage of Equatorial water.

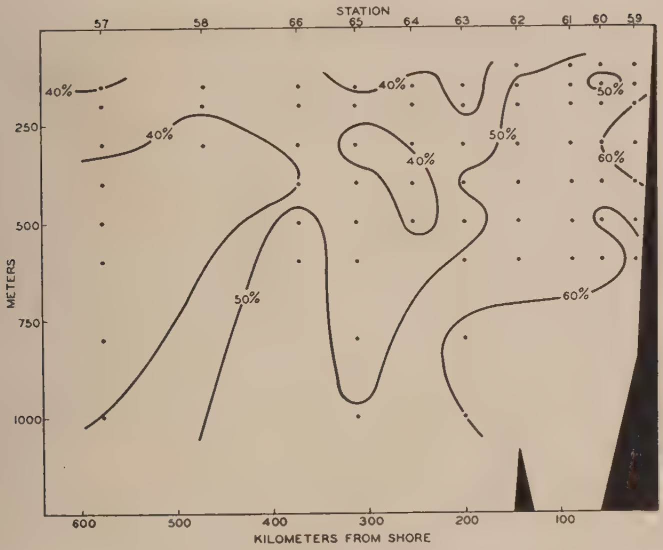

Figure 20. Section 4 off Point Dume, California, showing percentage of Equatorial water.

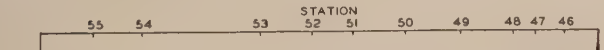

Figure 21. Section 3 off Monterey, California, showing percentage of Equatorial water.

percentages of Equatorial Pacific water obtained by entering in a diagram similar to that in Figure 17 the T-S relationships of the water at the various depths indicated in the sections, and then graphically interpolating the percentage composition at each depth. One feature of the distribution is common to all sections: the percentage is higher towards the bottom and towards the shore. This feature is especially prominent in section 6 (Figure 18) off Cedros Island, Lower California. In this region there is a remarkable intrusion of relatively warm, saline water at stations 81 and 82. In the charts of dynamic topography these correspond to the centers of two strong eddies. In section 5 (Figure 19) there is a central body of more northern water (e. g., low percentage of Equatorial water) which separates an inshore and an offshore region of higher percentage. This offshore region was, at station 77, near the center of a large eddy which appeared to bring water from the southwest into the region of observation. In section 4 (Figure 20) percentages vary from 40 near the surface and offshore to more than 60 inshore and at deeper levels. The same is true of section 3 (Figure 21) although the details of distribution are somewhat different. The two northernmost sections, 2 and 1 (Figures 22 and 23), show the lowest percentages, less than 25% of Equatorial water, but even these show some water of greater than 40%.

Figure 24 shows the percentages of Equatorial Pacific water at the 300 meter level. Again, in general, the percentages are higher inshore, the 50% curve extending as far north as Monterey, and there is a general decrease from south to north.

There is a good agreement between the distribution of the various percentages of Equatorial water and the known current pattern. The transport of warm, saline Equatorial water to the north appears to be largely accounted for by the inshore northward flow of the California Coastal Counter Current. Present data indicate that this current exists throughout the year at about 200 meters and below, and that above 200 meters it is encountered only during the winter months when it appears at the surface as a narrow, northerly coastal current (Tibby, in press). It is within the region immediately adjacent to the coast and at intermediate depths that the highest percentages are found. The general decrease in relative content of Equatorial water as the Counter Current flows north can be satisfactorily explained only on the basis of lateral mixing with the southward flowing waters of the California Current which were originally of Subarctic character and which show an increased content of Equatorial water toward the south.

It is shown here that the water at depths of from about 150 to 1000 meters off the west coast of North America is a mixture of two extreme

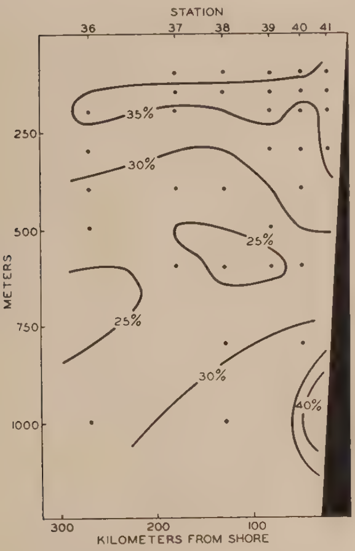

Figure 22. Section 2 off Cape Blanco, Oregon, showing percentage of Equatorial water.

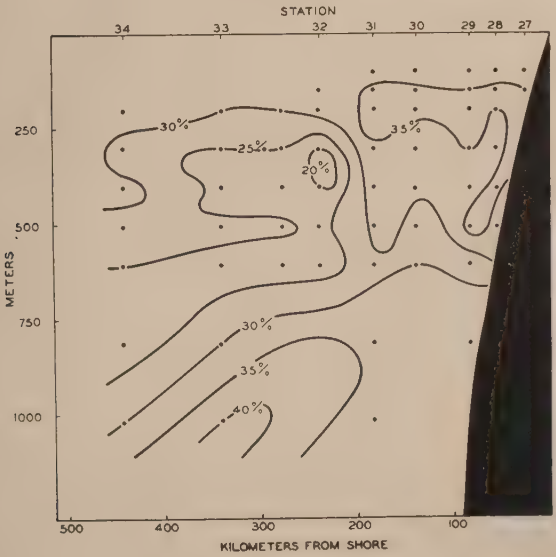

Figure 23. Section 1 off Cascade Head, Oregon, showing percentage of Equatorial water.

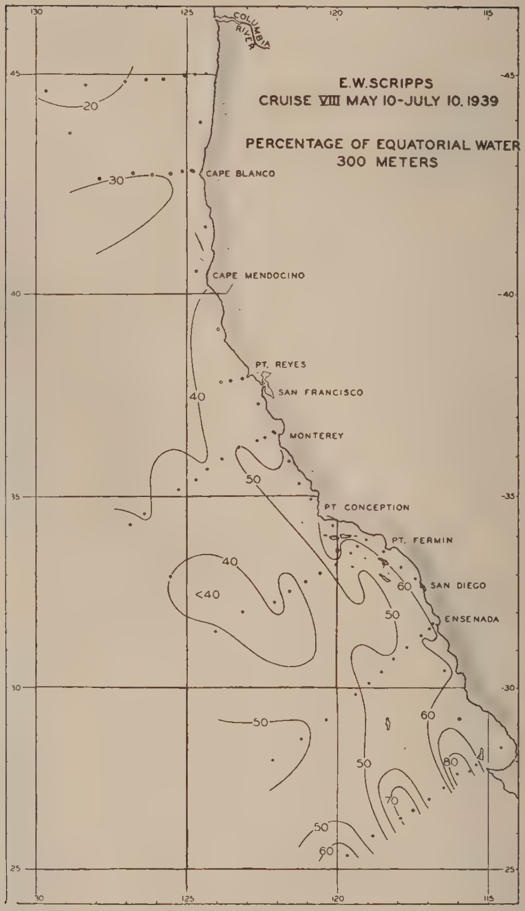
E.W.SCRIPPS
CRUISE VIII MAY 10-JULY 10. 1939
PERCENTAGE OF EQUATORIAL WATER
300 METERS
COLUMBIA RIVER
CAPE BLANCO
CAPE MENDOCINO
PT. REYES
SAN FRANCISCO
MONTEREY
PT CONCEPTION
PT. FERMIN
SAN DIEGO
ENSENADA
130
125
120
115
45
40
35
30
25
20
30
40
50
<40
60
70
80

Figure 24. Chart showing percentage of Equatorial water at 300 meters.

water masses which are defined as Subarctic North Pacific and Equatorial Pacific by characteristic T-S curves. The distribution of temperature and salinity over the region of the "E. W. Scripps" Cruise VIII (from Cascade Head, Oregon, to Cedros Island, Lower California, and to some 300 miles to sea) is expressed in terms of percentages of Equatorial water. These percentages are derived by a method based on the assumption that mixing between water masses takes place only along surfaces of equal σ_t. The distribution of these percentages is shown to be entirely consistent with the known pattern of flow in this region.

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Contribution No. 142

(Reprinted in U. S. A. from Transactions of 1940
of the American Geophysical Union)

TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

RESEARCH WITHIN PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL 1940 TO APRIL 1941

H. U. Sverdrup and Staff

(Contributions from the Scripps Institution of Oceanography, New Series, No. 142)

Emphasis will again be placed on the activities within the fields of submarine geology and ical and chemical oceanography, although researches within the biological fields cover the ter part of the work at the Scripps Institution of Oceanography. The compilation and dis- ions of field-data and the studies in the laboratory have been greatly facilitated by as- ance obtained from the Work Projects Administration Project No. 65-1-07-2317.

Last year's report concluded by mentioning that six cruises off the coast of southern Cali- ia were in progress in cooperation with the United States Fish and Wildlife Service. The s were carried out successfully in the period from March 5 to June 7, 1940. The cruises ted out at an average interval of 16 days, each cruise lasting about ten days and 32 to 41 ions being occupied, depending upon conditions of weather. The results of the cruises clear- emonstrate the changes during spring and early summer when upwelling farther north becomes and more intense and when the tongue of cold upwelled water at a distance of approximately iles off the coast of southern California becomes more and more prominent. The earlier es- ished relation between the distribution of diatoms and the character of the water was found xist on most cruises, but some conspicuous discrepancies occurred indicating that the dis- ution of diatoms must also depend upon the existence of other organisms. The distribution ardine-eggs which was examined in detail by members of the United States Fish and Wildlife ice showed a suggestive relationship to the character of the water-masses.

The network of stations was much closer on these cruises than on any previous cruise, the ions on a line being in general only 15 miles apart and the distance between station lines t 30 miles. In many instances stations were placed between the lines. In spite of this close ork few localized eddies were found, but a streaky distribution of temperature and salinity ailed with the streaks in the general direction of the currents. The currents are now being ined by R. B. Tibby who has developed methods for identifying a given water-mass such that location can be ascertained from cruise to cruise. The area under examination was so small, ver, that in most instances a water-mass could be traced from one cruise to the next only, ng been carried out of the region by the time of the third cruise.

A similar program is in progress this season. Again six cruises are planned in cooperation the United States Fish and Wildlife Service, but they will be spread over a greater length ime, the start of cruises being scheduled to take place at intervals of 24 days. Between standard cruises which are expected to last ten to 12 days, special trips will be made for purpose of examining in detail photosynthesis, problems in bacteriology, and the horizontal vertical distribution of sardine-eggs and larvae. The first standard cruise was completed een March 21 and 30, 1941. It showed a distribution of temperature differing greatly in de- from that at the end of March, 1940, the difference being that in 1941 much warmer water found close to the coast, probably due to the effect of numerous storms from the southwest. picture was more similar to that of February, 1938, indicating that this year the winter itions have prevailed longer than in earlier years from which comparable data are available.

Messrs. Fleming and Sverdrup have participated in the examination of the data from the ses of 1940 and have furthermore been engaged in examination of the general distribution of nt-nutrients in all oceans and the general character of the water-masses and currents of the ns. E. C. La Fond has conducted a considerable part of the routine computations related to cruises and has continued the supervision of the studies of wave-heights and currents at the of the Institution's pier and the measurements of sand-level along the pier and the adjoin- beach. The latter investigations have attracted more and more attention because of the in- asing interest in the protection and development of the beaches of southern California.

During the year Dr. L. Lek has worked at the Institution on problems in physical ocean- aphy and has particularly studied the water-transport by a number of the larger currents of oceans. Dr. H. R. Seiwell of the Woods Hole Oceanographic Institution has been a visitor ce November, 1940, and has worked up a number of his observations on internal waves.

In July and August, 1940, Dr. R. T. Young, Jr., of Worcester Polytechnic Institute, com- ted an apparatus for measuring in the laboratory the absorption of light in samples of dis- led water or of sea-water. Unfortunately, because the *E. W. Scripps* was having a new main

engine installed, no provision could be made for obtaining samples of sea-water from any
tance from the coast. A few samples were obtained by use of a motor-boat. The unfiltere
ples showed a marked but irregular decrease in the transparency of the surface-water on a
tance of 13 miles from the coast, and at two stations an irregular variation with depth w
found. Filtration increased with the transparency of samples from 60 to 70 per cent of t
pure distilled water up to 90 to 95 per cent. Young concluded that most of the observed
tion in transparency was due to suspended material which could be removed by a filter. I
hoped to continue the observations and, particularly, to find methods by which the relati
iations in transparency which can be measured directly at any station may be converted in
solute values.

At about 40 stations occupied on each of the six cruises made by the E. W. Scripps d
the first half of 1940, serial phosphate determinations to depths of about 500 meters wer
by E. G. Moberg and J. Lyman. The results have been prepared for publication and later w
correlated with the dynamical, physico-chemical, and biological conditions in the area in
gated. A preliminary examination shows a marked relation between phosphate-content and t
current-systems and water-masses. Because phosphate can be determined rapidly and on boa
ship, there is a good possibility that it can be used as an indicator of the origin and m
ments of water-masses.

A study has been begun by E. G. Moberg of the results of several thousand calcium-determinations made on serial water-samples from several regions in the Northeastern Paci
from the Aleutian Islands to Panama, including several hundred samples from the Gulf of C
fornia. From previous investigations here and elsewhere it has been concluded that in no
sea-water the ratio (Ca:Cl) is constant, but a preliminary study of the large body of data
available indicates an increase in the ratio with increasing salinity. It has not yet bee
definitely established whether this is true also at the surface. According to what is kn
the solubility-relations of calcium salts in sea-water, the opposite would be expected.

John Lyman has concluded an investigation extending over several years of the buffer-mechanism of sea-water. The complete solution of the problem for natural sea-water requi
knowledge of the magnitude of two dissociation-constants of carbonic acid and two of boric
as well as their respective variation with temperature and chlorinity. In the past such m
surements have been made separately to evaluate single constants, but use of the glass ele
for determination of hydrogen-ion concentrations without disturbing the sample under study
it possible to obtain continuous and highly accurate titration-curves of normal and carbon
dioxide-free sea-water, from which the four dissociation-constants can be calculated simul
ously. The results obtained will find application in analyzing a number of geological and
chemical processes taking place in the sea and on the sea-bottom.

A few years ago a study of methods for determining iodine in sea-water was begun, and
adaptation of one method was found to give reliable results, showing that in this locality
content of iodine is in the order of 0.05 milligram per liter. During last summer additio
studies of the iodine-content and of methods for its determination were made by Dr. W. L.
dick of Sacramento Junior College. From serial water-samples from depths to 800 meters it
found that, unlike the common plant-nutrients, the concentration of iodine is approximatel
stant at all depths.

G. F. McEwen reports that in addition to the usual work on advance indications of air
sea-temperatures and seasonal precipitation in Pacific coastal areas, a special study of t
Colorado River runoff was begun. This project, carried on through a cooperative arrangeme
with the Bureau of Power and Light of the Department of Water and Power of the City of Los
Angeles, has for its ultimate objective an understanding of the behavior of the seasonal ru
of the Colorado River, in relation to precipitation in the drainage-basins, that will lead
general forecasts of the runoff for periods of several years.

From the base-maps of the drainage-areas and location of weather-stations, studies ar
ing made of the correlation between the relatively short and somewhat fragmentary records
within these areas and the long continuous records at appropriate central United States We
Bureau stations. These investigations are intended to provide a convenient means of estim
the precipitation over any desired portion of the area.

One method of using such data for forecasting runoff is based upon the assumption of
regular and continuous replenishment of a stored supply of water to the atmosphere combined
its dispersion, partly in accordance with a random series of rare events. Another method a
the time series to represent numbers of certain rare events which occur in respective time-

vals (at random, with certain probabilities) and repeat themselves after certain periods of

A special study has been continued by Dr. Gorczynski with the help of McEwen concerning ty-percentages. These results have been represented on a large number of maps involving orld as a whole and on larger-scale maps of California and adjacent regions. The aridity- ntage equals (latitude-factor) x (precipitation-ratio) x (temperature-range). The latitude- r equals the cosecant of the geographical latitude times a factor that limits the aridity- ntage to 100 per cent for the most arid region of the Sahara Desert. The precipitation- equals (maximum minus minimum annual precipitation) divided by the average for the inter- Problems of reducing this ratio to a standard (50-year) interval and of making the proper ctions when the three highest and three lowest values of the annual precipitation are used been investigated by McEwen. He has nearly completed an extensive investigation of such stical problems, including the standard errors of the precipitation-ratio. Convenient s and diagrams prepared for the application of these results were used in the computations he Gorczynski maps. McEwen's investigations led R. D. Gordon to make supplementary studies, et completed, of the correlation of simultaneous errors involved in two different estimates e same quantity.

Beginning with very general assumptions concerning (turbulent) mixing processes in a fluid, n has begun an application of the invariant-integral theory of Édouard Goursat which promises ve significant results in connection with such problems as the determination of "virtual sion-coefficients" in the ocean, or the study of production- and consumption-processes tu (without knowledge of the magnitudes of diffusion-coefficients). The study begins with ear partial differential equation (or form) known to be elliptic, but with unknown second- coefficients, and one or more particular solutions are supposed known presenting, for ex- , concentrations of salt, oxygen, or temperature.

Daily observations of sea-surface temperature and daily collected water-samples have been ned from five localities on the California Coast, exclusive of those taken at the Scripps tution Pier. The salinities of the samples have been determined by the specific-gravity i. Other observations of surface-temperatures have been obtained from the U. S. Lightship rs Sequoia and Lupine, and from tuna boats. The cooperation of organizations and personnel eatly appreciated.

Conferences have been held with Dr. O. E. Sette for the purpose of arriving at suitable stical methods of dealing with practical problems as they arise in his investigations of rdine-problem. Some assistance likewise has been given to local biologists in connection heir mathematical and statistical problems.

The sediments division of the Scripps Institution, in charge of R. Revelle, has been occu- rincipally in carrying out routine mechanical and chemical analyses on the large numbers tom-samples collected in the Gulf of California and in the southern California region in years. Studies of the sulphur-cycle in marine sediments have been continued and formed the major problems investigated on the expedition of 1940 to the Gulf of California. ores of green mud from this area frequently stink of hydrogen sulphide from top to bottom is found, indeed, that near the bottom of many cores all the sulphate in the interstitial has been reduced to sulphide. No iron sulphide is present, however, suggesting that h diagenetic processes the iron present in the sediment has been locked up in a compound oluble than iron sulphide.

. L. Natland continued his work on the foraminiferal remains present in the bottom-deposits collections of the Scripps Institution. A study of 400 species of foraminifera in 170 s collected by the United States Navy and the United States Coast and Geodetic Survey in nama Area has now been completed and it is possible to assay the relative effects of dif- ecologic factors by comparison of the faunas found in these tropical waters with those off southern California.

uring the summer and fall of 1940, F. P. Shepard completed his reports to the Geological y of America on field-work conducted mainly in 1938. He continued his observations on lines, repeated numerous soundings in the La Jolla Canyon, and collected a great amount of n rip-tides and rip-currents for a paper which was submitted to the Geological Society of a.

n the E. W. Scripps cruise to the Gulf of California in 1939 it was found that in this re- t the present time are reproduced many of the conditions which characterized certain land-

areas of great geologic interest in the past. Accordingly, a second expedition under the j
sponsorship of the Geological Society of America and the Scripps Institution was organized,
the three months of October, November, and December, 1940, were spent in Lower Californian
waters. This expedition had a single general purpose, namely, to study the geologic proces
which are or have been active in the Gulf of California through a coordinated investigation
the recent geologic history of the land, of the bottom-topography and sediments, and of the
ture of the marine environment. The geological and oceanographical work carried out at sea
under the joint supervision of Roger Revelle and Francis P. Shepard. Sydney Rittenberg was
charge of the chemical and bacteriological studies made on the Gulf waters and on sediment-
collected from the sea-bottom, while Kenneth Emery and Robert Dietz assisted in all the ope
at sea and were particularly responsible for the taking of cores and other samples of botto
sediments. The geology and paleontology of the island and land areas in and surrounding th
Gulf were studied by Charles A. Anderson and J. Wyatt Durham.

From the geologic work on shore it is possible to conclude that the Gulf of California
isted in essentially its present form before late Pliocene time. Considerable tectonic act
has taken place since the Pliocene, however, and has probably been responsible for the form
or modification of many of the deep troughs and basins of the Gulf floor, as well as for th
present outlines of the islands and surrounding coasts.

During the course of the expedition the fathometer echo-sounding machine was run almos
continuously whenever the vessel was under way. Records of about 25,000 soundings were obt
greatly amplifying the results of the cruise of 1939 and establishing many features of the
marine topography in a region where previous depth-measurements were almost lacking. Speci
studies were made of supposed submarine fault-scarps and fault-troughs, of submarine canyon
and of submarine terraces. The Gulf of California appears to be essentially a broad fault-
trough, roughly V-shaped in cross-section, within which a series of narrow basins have been
formed by faulting subsequent to that which gave rise to the Gulf as a whole. Deep terrace
served along the sides of the Gulf can be explained in part as remnants of the old floor pr
to the development of the inner troughs. The recency of tectonic movement is indicated by
absence or narrowness of the continental shelf in many places and by the relative scarcity
canyons cut into the submarine slopes.

Approximately 100 cores and 120 large-snapper samples of bottom-sediments were taken.
of the outstanding results of this work was the collecting of cores considerably longer tha
previously taken in the deep waters of the open sea. Several cores over 15 feet long were
covered and one was nearly 17 feet in length. These great lengths were in part due to the
tively soft character of some of the bottom-muds and in part to the ingenuity of Emery and
who devised several important improvements in the coring apparatus. Core-barrels 20 feet l
and 2-1/2 inches in diameter were employed, and these were equipped with liners and core-ca
of thin flexible celluloid instead of the metal or glass formerly used.

The floor of the Gulf of California is unique so far as the present sea-bottom is conc
in that over many thousands of square miles it is covered with a green, finely laminated, h
organic diatomaceous mud which is apparently the modern analogue of the Miocene diatomaceou
shales in the California coast ranges. On drying a core of this diatomaceous mud the lamin
are clearly seen as alternating white and green bands about 0.2 to 1.0 mm thick, which beco
more closely spaced as the bottom of the core is approached, probably owing to compaction.
the laminations represent annual layers corresponding to seasonal fluctuations in the produ
of plankton-diatoms in the overlying waters, the rate of deposition of these relatively loo
muds may be calculated as about one foot in 350 years.

The seasonal character of phytoplankton-production in the Gulf of California is abunda
demonstrated by observations made on the two E. W. Scripps expeditions. On the cruise of 1
which took place in February and March, the waters over large areas were reddened and opaqu
great was the phytoplankton-population. When the expedition of 1940 first reached the Gulf
surface-waters were warm, blue and clear, the phytoplankton-population and the content of n
ent salts were very small, and interchange with nutrient-rich deep waters was prevented by
stable density-stratification accompanying the high temperatures of the surface-waters. Wi
the development of northwesterly winds of gale force, which began in November, repeated mea
ments of the vertical distribution of temperature, salinity, oxygen, phosphate, and silica
showed that the warm surface-waters were being blown southward while upwelling of cold wate
low-oxygen and high-nutrient-salt content, and mixing of surface and subsurface waters were
ing place. At the same time quantitative samples showed a marked increase in phytoplankton
population and small patches of red water were seen in December.

That the diatom-frustules produced in the winter and spring months quickly settle through water was evidenced by repeated measurements of the amount of remains of diatoms in the at depths of 1,000 meters or more. In October, when the surface-waters were bare of phyto- kton, practically no remains of diatoms were found in the deep water; after plankton-produc- had proceeded for a few weeks near the surface, it was possible to collect many thousands iatom-frustules per liter even at depths greater than 1,000 meters.

Large-scale phytoplankton-production and huge diatom-populations occur elsewhere, yet the om-deposits off the American west coast, for example, are not notably diatomaceous because frustules settling into deep water become dispersed and dissolve before reaching the bottom. he last analysis, the rate of silica deposition on the bottom must be exactly equal to the ss of silica brought into any region over that carried out of it by water-movements. From point of view, the formation of siliceous deposits on the floor of the Gulf must be due es- ially to the character of the circulation and the presence of these deposits can be taken as ence that silica-rich water flows into the Gulf at depth and that silica-poor water leaves t the surface. This is confirmed by the observed increase in concentration of silica in the water from the mouth of the Gulf to the region west of Guaymas and by the fact that the waters of the Gulf have about 30 per cent more silica per unit of volume than do those of open sea.

The mechanism of silica deposition has been discussed at considerable length because it tifully illustrates the unity and interrelationships of the sciences of the sea. Several r kinds of investigation of geological processes in the water and on the bottom were carried on the expedition. These included current-measurements from the vessel anchored in depths ,000 to 2,000 meters, measurements of the amounts of decomposable organic matter in the water on the bottom, of the vertical distribution of bacteria in cores and in the water-column, rminations of pH, sulphide and sulphate content. Subsequent studies comprised the distribu- of organic pigments by Dr. D. L. Fox and L. J. Anderson, and examination of gaseous hydro- ons by Dr. B. Washburn of the United Geophysical Company of Pasadena. Because of the great th of the cores collected, the variety of sediments encountered, and the high organic-matter ent of some of the muds, the Gulf of California represents an excellent field-laboratory for study of diagenesis.

pps Institution of Oceanography,
University of California,
La Jolla, California

Contribution No. 143

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elp Cutting

*Are Present Methods of Harvesting This Sea Weed Detrimental to the State's Marine Fisheries? Here Are the Answers**

By CLAUDE E. ZOBELL, Marine Microbiologist,
Scripps Institution of Oceanography,
University of California

IDERABLE INTEREST has been taken recently
the biological consequences to California ocean
of kelp harvesting and its effect on beach erosion.
as we are with a wealth of terrestrial resources in
ntry we have given far too little attention to the
ation and intelligent use of the great wealth of the
s of the sea. Like liberty, we rarely appreciate
sources until faced with the possibility of their

itself has considerable commercial importance and
been claimed that kelp beds have a far-reaching
n marine fisheries, beach erosion and other condi-
the sea. These problems have been made the sub-
careful study by the Scripps Institution of
graphy and other agencies.

e are several varieties of seaweeds or rockweeds
are known as kelp. Four of these, *Macrocystis*
a, Nereocystis luetkeana, Pelagophycus porro and
fistulosa, are commonly called "giant kelps"
of their great size. Only *Macrocystis* is exten-
harvested in California. Scattered dense beds of
ing an aggregate area of from 120 to 150 square
ccur in shallow water off the coast of Southern
nia and around the Channel Islands. Sparse
s of *Nereocystis* and *Pelagophycus* often grow
beds of *Macrocystis* although north of Point Sur
re large beds of *Nereocystis.* *Alaria* is the most
nt along the Alaskan coast.

California kelp industry depends almost exclusively
lacrocystis. It has proved to be valuable for its
ve properties for man and animals and especially
content of algin, solvents and minerals.

n is a dispersing agent which is widely used in the
hemical and textile industries. Several products
d from kelp are used in munitions. During the
orld War we depended largely upon kelp as a
of potash, iodine and acetone which we had been
ng from Germany. Although kelp is a good fertili-
is an expensive one, therefore virtually no kelp is
this country for this purpose.

ocystis is a vigorous growing perennial. It may be
ed three or four times a year without any danger
usting it. If the stipes (stems) are properly cut
arp knives or sickles near the water surface, new
atocysts (float-bladders) and fronds (leaves)
grow again. If, however, the kelp is torn loose by
or otherwise, the
sts or root-like struc-
re broken loose and
tire plant may be
nently destroyed.
it might be several
s or a few years, de-
g upon various con-
s, before it is replaced
ther kelp plant from
ating spores from
the kelp reproduce.
ely, if ever, do the
rcial kelp harvesters
e kelp loose from the
sts because it is
to harvest it by cut-
e stipes two to four feet below the water surface. Moreover, the harvesters are primarily interested in the fronds which grow at the surface. The kelp harvesters realize that to pull up the holdfasts of the kelp would be analogous to the orchardist harvesting his fruit by cutting down the trees. Furthermore, depth at which cutting is permitted is regulated by the California Division of Fish and Game.

When kelp is not cut it tends to grow old like any other vegetation, and with age it dies and rots. In sound agricultural practice trees or shrubs are trimmed at frequent intervals, and other plants are harvested to insure new vigorous growth. Those who have studied the kelp believe that similar practice is best for it.

Old kelp plants tend to become rotten and large patches may be broken off or pulled out by the roots (holdfasts) during storms. It is primarily such rotten kelp which one sees washed ashore after a storm. The young, vigorous, growing kelp is rarely broken loose during storms.

There is evidence which suggests that old kelp in the denser beds is more susceptible to bacterial infections. In 1934 I did some work on kelp from the Catalina region where cutting had been prohibited. During the warm summer months it started to rot and large acreages rapidly disappeared. Investigations revealed the presence of a marine bacterium which attacked the kelp.

As soon as the pneumatocysts or float-bladders are injured the entire kelp plant sinks to the bottom. During periods of unusually warm water large acreages of kelp have been observed to disappear almost overnight probably due to the bacterial injury of the pneumatocysts.

This seems to be Nature's way of "trimming" but it is a wasteful one because not only is all of the kelp in the region destroyed but it may require several years for it to be replaced.

The U. S. Fish and Wildlife Service is interested in the conservation and husbandry of our aquatic resources. After years of study its experts recommend the judicious and systematic cutting of kelp. This is also the recommendation of a commission headed by Captain W. C. Crandall which made an extensive survey of Pacific Coast kelp during the first World War under the auspices of the U. S. Department of Agriculture. During 1917-18 nearly one million tons of kelp were harvested off the coast of Southern California where it was processed for strategic war and food materials. No harmful effects were noted although more kelp was harvested during those years than any time since.

Judicious harvesting under close supervision by State officials is the policy being followed by the California State Division of Fish and Game, which has legal jurisdiction over the kelp beds of this State.

There is no evidence that any commercial or game fish of any importance depend upon the kelp for their existence. Few if any of them are known to

A kelp cutting and harvesting barge of the San Diego region. In the foreground may be seen float-bladders and kelp fronds above the water's surface live, breed or feed extensively in kelp beds. Certain fishes, such as kelp blennies, flying fishes and garibaldi, for example, obtain some food from kelp and from organisms associated with kelp but it should be emphasized that more than 99 per cent of the food of marine fishes comes directly or indirectly from plankton organisms (small free-floating plants and animals).

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* Contribution from Scripps Institution of Oceanography (La Jolla, California), New Series No. 143.

Occasionally smaller game fishes may be pursued to kelp beds where they take temporary refuge from a larger predator, but again it should be kept in mind that there are hundreds of other kinds of marine plants at the bottom of shoal waters which serve equally well for this purpose. Since it is practical to harvest only about 50 per cent of each kelp plant, the other 50 per cent of the plant, unobserved from the surface, remains there as a refuge for those fish which may need it.

Some fisherman contend that game fishes such as the yellowtail, bonito, barracuda, bass and others are taken primarily around kelp beds. However, this does not prove that the kelp is responsible for the fishes being there although it might serve as a good "landmark" for the fishermen. *Macrocystis* grows primarily over rocky bottoms where there is little or no sand, in water which is from 30 to 60 feet deep and in a region where there is a continual swell. Many kinds of fishes congregate in a similar environment regardless of the presence or absence of kelp. Commercial fishermen and many sportsmen find the yellowtail, barracuda, bonito and bass in abundance in regions far removed from kelp beds.

Richard B. Tibby said in a report of his investigation of this matter for the State Division of Fish and Game:

"There is no connection between kelp beds and fishes such as the sardine, mackerel, tunas, yellowtail, barracuda, etc. Kelp beds play no part in the life history of any of these fishes.

"The eggs and larvae of these fishes are pelagic— that
is, they float free in the water at or near the su
and are carried here and there by the curre
spawning should take place within a kelp bed, t
and larvae would be quickly dispersed and carrie

An employee of the Scripps Institution collecting a sample of sea water for chemical analysis in connection with the kelp investigation. The temperature of the water is registered by the reversing thermometers shown beside the Nansen bottle

A tangled mass of kelp fronds with their
pneumatocysts (float-bladders) near surface of cal
Individual plants often attain a length exceeding

"Eggs of the kelp bass and other fishes commo
ciated with kelp beds are also pelagic. The
destruction of the beds might have an untoward
the adult kelp-dwelling fishes but it is extremely
that any harvesting of kelp as it is now done, n
how extensive an area may be involved, has any
effect on these fishes and certainly not on pelagic s

P. S. Barnhart of the Scripps Institution of
graphy declares that during the last 30 years
observed much less kelp washed up on the beach
the kelp harvesters have been working in the reg
prior to their activities. He attributes this to t
vigorous and healthy condition of the kelp caused
odically cutting or trimming it. Most of the kel
is washed ashore is old and partly rotten and s
evidence of ever having been trimmed.

This authority on marine organisms believes th
more of this old kelp is washed ashore to waste
than the total amount cut by commercial kelp ha
Barnhart said:

"It is the general opinion of those who have stu
problem that kelp harvesting as now practiced
undesirable effects on the kelp beds or on the fis
live therein. Fishermen themselves and not the k
vesters are to blame for any decrease in the abun
game fishes. The hundreds of thousands of tons
dines, mackerel and other fishes which have bee
from the sea by devious methods without any tho
the future is beginning to deprive the larger gam
of food."

Unless the kelp is wantonly wasted there is litt
bility of depleting the kelp beds. It is because
commercial value of the important beds such as th
La Jolla, Point Loma, San Clemente, Oceanside a
where along the California coast, however, that k
ting and harvesting are being judiciously contr
the State Division of Fish and Game.

Cognizant of this, the Division drafted provisio
fish and game code which require that "every
engaged in harvesting kelp . . . must have a
therefor." Code section 583 provides that "if,
time, the harvesting of kelp will tend to destroy o
any kelp bed or beds, or parts thereof, or shall
impair or destroy the supply of any food for fish,
and Game Commission shall serve on every person
to harvest kelp a written notice that said kelp bed

thereof, shall be closed to
g of kelp for a period not to
e year.''

gh biologists are aware of no
hy kelp harvesting as now
should be curtailed, they
at the problem should be
ore thoroughly. There are
s in our knowledge of the
hich influence the growth of
ch a study, for instance,
e it possible to greatly in-
amount of kelp which can
ted economically. The ap-
of scientific principles to the
f agriculture have increased
the productivity of the soil,
ulture may be just as suscep-
ientific treatment.

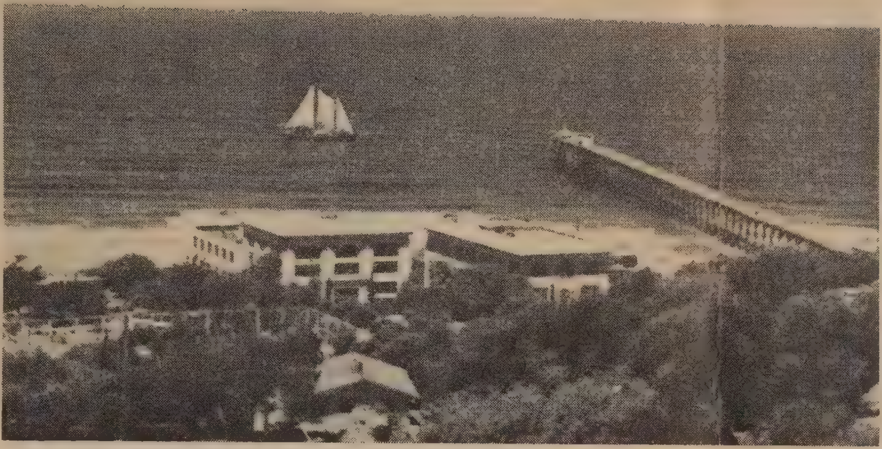
ttle is known about the ef-
lp cutting on beach erosion.
lp does tend to break the
e incoming swell, as claimed
laymen, it seems highly im-
that harvesting the upper-
ion of the kelp will make
ference. Dr. Harald U.
director of the Scripps In-
f Oceanography, points out:

erosion results from high
swells and the smaller sur-
s—the white caps—have no
his is definitely established
rous measurements at the
stitution of Oceanography.
smooth the ripples on the
d acts in this respect like
is, indeed, doubtful whether
exercise any appreciable
he long swell.

e casual observer,'' he con-
he cutting of kelp appears
ce wave action because if
five feet of the kelp have
way the ripples and white
ot disappear when the swell
kelp beds. But the im-
estion is whether the swell
ced by the cutting of the

w of the fact that within
ell the wave motion reaches
tom and the energy of the
arly the same at all depths,
lt to see how the removal of
near the surface can ma-
ange the possible resistance
kelp offers to the swell.
t little is known about the
ch cause erosion it appears
that the harvesting of kelp
or no effect on beach ero-

the last two years LaFond,
nd Williams of this insti-



Principal buildings of the Scripps Institution of Oceanography at La Jolla, a branch of the University of California devoted exclusively to the study of the sea, its movements, its inhabitants, its constituents and its relation to man. The research vessel, ''E. W. Scripps,'' is shown at the left of the 1000-foot pier

tution have been making daily observations on the amount of kelp on the beaches along the La Jolla Shores and a few scattered observations at Del Mar, Torrey Pines and Pacific Beach. They have found no correlation between the amount of kelp on the beaches and wave height nor has the amount been related to kelp cutting activities in the vicinity.

There is evidence of a seasonal cycle of abundance with somewhat more kelp being deposited on the beach during the summer months beginning with April than during the winter months beginning with September. It may be significant that no kelp was harvested in the vicinity during June, July and August, 1940, a period when the most kelp was found on the beaches.

There was no correlation between spring tides and kelp deposition but following days when the average wind velocity exceeded 10 miles per hour there was on an average 40 per cent more kelp piled up on the beaches than when the wind velocity was less than 10 miles per hour. The investigations are being continued.

All aspects of the problem should be investigated more thoroughly, including careful surveys of the area of kelp beds from year to year, of the rate of growth of kelp together with the factors which influence its reproduction, of the relation of the kelp beds to the fauna which they harbor and of the accumulation of actual records on the effect of kelp cutting on the catch of fish as well as on beach erosion.

Inasmuch as a multiplicity of interrelated factors are involved it will require that scientific observations be made over a period of several years. Such investigations are now in progress at the Scripps Institution of Oceanography and provisions have been made for at least one scientist to devote his full time to the problem during the coming year in cooperation with other staff members. Due to the magnitude of the problem and its multifold intricacies the cooperation of other research agencies is solicited for the making available of relevant data for the cumulative records.

As each year more and more uses are being found for kelp and other seaweeds, the harvesting and processing of these products promise to become important industries. Although kelp contributes relatively little to the $40,000,000,000 worth of marine products of commerce taken from the oceans of the world each year, certain by-products have strategic applications for which we have no known substitutes.

Therefore the conservative use of kelp is imperative and since it is unlikely that the value of such products will ever be commensurate with the value of our recreational beaches and fisheries, the latter must not be jeopardized by kelp harvesting.

Contribution No. 144

(Reprinted in U. S. A. from Transactions of 1941
of the American Geophysical Union)

PAPERS, SECTION OF HYDROLOGY

NATIONAL ACADEMY - RESEARCH COUNCIL BUILDING
FIRST SESSION, 9:00 A.M., MAY 1, 1941

CRITERIA FOR RECOGNITION OF SEA WATER IN GROUND-WATERS

Roger Revelle

(Contribution from the Scripps Institution of Oceanography, New Series, No. 144)

In semiarid regions near the seacoast excessive pumping of wells is liable to cause salt-
intrusion either from the ocean itself or from relatively impervious marine sedimentary
surrounding the aquifer which yields ground-water. Since the ground-waters of semiarid
ns commonly have a relatively high and variable concentration of dissolved salts, a slight
ase in concentration, such as is found by measuring resistivity [see 6 of "References" at
f paper], may not alone be sufficient to prove the presence of sea water. On the other hand,
ground-waters usually differ widely from sea water in composition, it might be thought
changes in the proportions of different chemical components of well-waters in the direction
a water could be used to detect the beginnings of admixture. Actually, however, the ob-
d changes in composition of well-waters may be quite different from those that would occur
mple mixing with a small portion of sea water owing to the modifications which sea water
f may undergo as it passes through the ground or through marine and estuarine sediments.
bsence of those proportional changes which would result from a direct mixture of sea water
round-water cannot be taken as a warrant for disregarding other signs of salt-water en-
hment.

The modifications in composition which sea water can undergo on passing through soil or
ent may be divided for convenience into three categories: Those which affect the propor-
between positively charged ions (cations) alone; those which affect only the proportions
en negatively charged ions (anions); and those which result in changes of equal significance
both cations and anions. In the first class are modifications resulting from base exchange
en the water and the minerals of soil or sediment, in the second category are changes in
ate and bicarbonate content due to processes of sulphate reduction and substitution of car-
or other weak acid radicals, and processes of solution and precipitation which affect the
ive amounts of both positive and negative ions make up the third group. Only solution and
pitation result in gain or loss of total salts considered as concentration values. In
sses of base exchange, oxidation-reduction, or acid replacement, the total equivalent amount
ses and acid radicals remains unchanged, because ionic balance must be preserved. The per-
ge by weight of different salt components is altered, however, and the total dissolved
s in part per million may be increased or decreased.

Alteration of sea water by base exchange--Although the total amount of hydrogen, sodium,
sium, calcium, and magnesium in any given clay or soil is roughly constant, the proportions
en these various bases differ widely, depending on the composition of the water with which
oil is in contact. The bases that can be interchanged between the water and the soil are
d replaceable bases. Kelley and Liebig [3] found that if a soil is repeatedly leached with
ution containing several cations, such as sea water, a state of equilibrium is finally at-
d, that is, when the soil is placed in contact with a new portion of the solution neither
oil nor the water gains or loses any cations whatever. It is known also that base-exchange
ions take place rapidly, and it therefore seems reasonable to conclude that when any soil
diment containing clay, organic matter, or other base-exchange material is placed in con-
with water containing dissolved salts, an equilibrium partition of the various bases present
en the water and the soil is quickly reached. It might be expected that at equilibrium the
would be present in the same proportions in both the water and the soil, but this is not
ase. The cations differ widely in "base-exchange activity," that is, in their tendency to
ce each other on and within the crystal lattices of clays or other base-exchange minerals.
other things, the base-exchange activity of a cation depends on the size and degree of
tion of the ion, and to some extent, also, on the character of the minerals involved in the
ion. In general, calcium, potassium, and magnesium have a far higher base-exchange activ-
han sodium. For example, the percentage of replaceable magnesium exceeds that of sodium in
y in equilibrium with sea water, even though the equivalent amount or reacting value of
m in ocean water is over four times as great as the reacting value for magnesium. Soils in
sodium makes up more than 60 per cent of the replaceable bases can only be obtained by
ing with an almost pure sodium solution [2].

For any given initial composition of water and sediment it should be possible to predi the approximate equilibrium composition of the water and the proportions between the exchan able bases present in the sediment. This may be done by utilizing the principle of mass-equilibrium as it applies, for example, to the partition of a mixture of gases between a li solvent and the gas-phase in contact with it. Just as the ratio between any two gases in t solvent is in direct proportion to the ratio in the gas-phase multiplied by the ratio of th ubilities of the two gases, so the proportion of any two bases in the soil colloid should b constant ratio to the proportions in the water multiplied by the ratio of the base-exchange activities of the two bases. That is, if we take sodium and calcium as examples:

$$(\text{Pct Ca}_{\text{soil}}/\text{pct Na}_{\text{soil}}) = (K_{\text{Ca}}/K_{\text{Na}})\ (\text{pct Ca}_{\text{water}}/\text{pct Na}_{\text{water}})$$

where the terms K_{Ca} and K_{Na} may be taken to represent the coefficients of base-exchange act of calcium and sodium, respectively, and the terms $\text{pct Ca}_{\text{soil}}$, $\text{pct Ca}_{\text{water}}$, etc., refer to p centage of total replaceable bases in the soil or the total bases in the water, considered equivalents. To a first approximation, at least, this relation will hold, regardless of th solute concentration of the solution, the base-exchange capacity of the soil, or the relati amounts of other cations.

It is not possible to arrive at absolute values of the base-exchange activity coeffici of individual cations. Approximate ratios between the activities of any two major ions may calculated, however, from the data given by Kelley and Liebig [3] for the average percentag the replaceable bases in two clays in equilibrium with sea water. These data are shown in 1, together with the calculated ratios between activities.

Table 1--Approximate ratios between activities of major ions

Item	Percentages of total replaceable ca			
	Ca	Mg	Na	K
Sea water (Lyman and Fleming [4])	3.4	17.6	77.4	1.6
Average of two clays in equilibrium with sea water (Kelley and Liebig [3])	15.3	41.5	36.6	6.6
Ratios of base-exchange activities, referred to sodium, that is, $(K_{\text{Ca}}/K_{\text{Na}})$, $(K_{\text{Mg}}/K_{\text{Na}})$, $(K_{\text{K}}/K_{\text{Na}})$	9.5	5.0		8.7

Because of the paucity of observations and the variability in behavior of different ba exchange materials, little reliance can be placed on the actual numerical values for the ac ratios. They merely serve to emphasize the fact that sodium has from five to ten times as a tendency as either calcium, magnesium, or potassium to remain or enter in solution at the pense of the other bases when in contact with base-exchange materials.

Where the proportions between calcium, potassium, and magnesium are relatively consta the percentages of sodium in the soil and in the water have the relationship indicated by t following equation.

$$\left(\frac{\text{pct Na}_{\text{soil}}}{100 - \text{pct Na}_{\text{soil}}}\right) = \left(\frac{K \times \text{pct Na}_{\text{water}}}{100 - \text{pct Na}_{\text{water}}}\right)$$

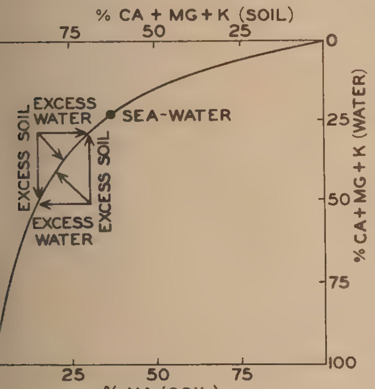
in which K is a constant. This equation may be transformed algebraically to give

$$\left(\frac{1}{\text{pct Na}_{\text{water}}}\right) = \left(\frac{K}{\text{pct Na}_{\text{soil}}} + \frac{1}{100} - \frac{K}{100}\right)$$

From Table 1 it may be calculated that K for sodium varies between 0.1 and 0.2. In se water and all other solutions having the same proportions between calcium, magnesium, and p tassium, K = 0.168. Exactly analogous relationships exist between the proportions of othe bases in sediments and interstitial waters, except that for calcium, magnesium, and potass is considerably greater than one. The percentage of replaceable sodium which may be prese a sediment or soil in equilibrium with any given percentage of sodium in an interstitial wa solution in which K = 0.168 is shown in Figure 1. Whenever the initial percentage of repla able sodium in the sediment is higher than the equilibrium value (about 37 per cent for se water), the solution will gain in sodium and lose other bases; when the sediment originall less than the equilibrium proportion of replaceable sodium, the water will lose sodium and re other bases in equivalent quantity. The extent of the changes undergone, respectively, e water and the sediment will depend on the relative quantity and replaceable base-content e sediment as compared with the concentration and quantity of the water. When a small t of sea water or other solution enters an aquifer, the equilibrium proportion of bases in ater will be virtually the same as that of the ground-water previously present there. On ther hand, a large quantity of water will bring the sediment into equilibrium without it-appreciably changing in composition, while when approximately equal amounts of water and ent or soil are present there will occur profound changes both in the replaceable bases of ediment and in the proportions of the different cations in the water.

Fine-grained soils of semiarid regions may contain from 5 to 40 or more milliequivalents of ceable bases per 100 grams, depending on the content of colloidal material and the character e clay minerals present. Undiluted sea water contains about 59 milliequivalents of bases 00 grams, an amount of only slightly greater magnitude, when it is considered that usually than a third of a soil-water mixture will be water. A permeable underground water-bearing um may contain smaller quantities of replaceable bases per unit-weight than the overlying , but enough colloidal material will usually be present to allow for major alterations in a ion newly entering the stratum and replacing the water previously present therein.

When the base-exchange capacity and amount of soil, the amount of water, and the total amount of each base involved in a base-exchange reaction are known, it is possible by means of simultaneous equations to calculate the final concentration at equilibrium of all cations in the water and the proportions between the bases in the soil. These complete data are seldom if ever available, however, in considering problems of salt-water intrusion. Neither the route followed by the water nor the quantity and character of the sediments through which it has passed can be known with certainty. Consequently, changes in the ratios between different bases observed in well water cannot usually be used as valid criteria of the presence of sea water, nor can the absence of such changes be taken as evidence that sea-water contamination has not occurred. The ratio between sodium and magnesium may under certain circumstances prove useful in detecting the presence of "fossil" sea-water derived from ancient marine sediments, as analyses by Case and others [1] indicate that at least in oil-field waters magnesium is very low compared with sodium. This is probably owing to a change of state of the magnesium in the sedimentary clays in contact with the water from a replaceable to a non-replaceable form during the long years since these sediments were first laid down by the sea.



1--Equilibrium-percentages of sodium soil and interstitial water (arrows icate modifications that will occur n water of different composition is ced in contact with the soil)

Alteration due to sulphate reduction--Oil-field waters, which are usually considered to be l sea-water trapped in marine sedimentary rocks, often have little or no sulphate, in con- to sea water in which the amount of sulphate by weight is about one-seventh of the ide. Likewise, the interstitial waters of recent marine and estuarine sediments have been ved by Murray and Irvine [5] and by Rittenberg and Revelle [9] to be often extremely low in ate. The first-named workers found that in the waters investigated by them the amount of ate lost was just balanced by a gain of "titratable alkalinity," that is, essentially in bonate content. These alterations in the composition of sea water in contact with sedi- containing organic matter were shown to result from the bacterial reduction of sulphate o hydrogen sulphide, and the concomitant oxidation of some of the organic matter to carbon de, as indicated in the following schematic equation.

$$3\ Na_2SO_4 + C_6H_{12}O_6 \xrightarrow{bacteria} 3\ H_2S + 6\ NaHCO_3$$

it is assumed for simplicity that the organic matter oxidized is entirely glucose.

Since sulphate reduction can and probably does take place wherever anaerobic conditions and there is a supply of oxidizable organic matter, it should be expected that sea water

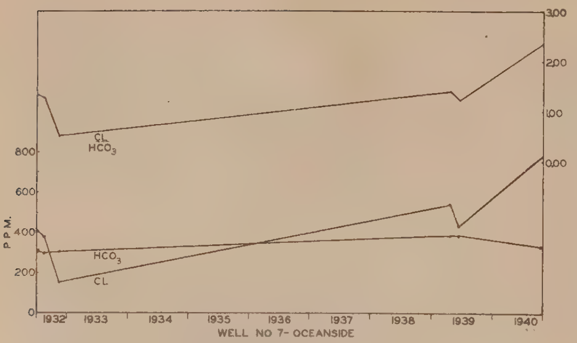


Fig. 2--Increase in (Cl/HCO_3)-ratio in a well near Oceanside, California

penetrating into an aquifer throu layer of marine or estuarine sedi will often lose at least part of sulphate content and gain a corre ponding amount of bicarbonate ion.

Alteration due to solution a precipitation--Under certain condi tions, on the other hand, the sul content of sea water in contact w soil or sediment may be increased. Posnjak [7] has recently shown th sea water can hold about three ti as much calcium sulphate as it ac ly does contain. Thus, ocean wate contact with gypsum or anhydrite, common constituents of certain se ments, will gain as much as 75 pe cent of its initial sulphate cont and at the same time the calcium content will be tripled. If the pH is about 8, calcium car bonate will then be precipitated and still more sulphate may be dissolved. The precipitati calcium carbonate may also accompany the process of sulphate reduction, particularly if this process takes place under sufficiently alkaline conditions, so that part of the bicarbonate duced is converted to carbonate ion. The actual solubility product of calcium carbonate in water is not accurately known, but it is generally agreed that at a pH of 8 or above and at temperatures greater than 20° C, normal sea water is saturated with calcium carbonate [11, and that consequently an increase in either calcium or bicarbonate ion will tend to bring a precipitation.

Of all the major ions occurring in sea water only chloride is unaffected by the process of modification which have been described. Chloride is the dominant ion of ocean water and usually plays only a minor role in ground-waters; hence an increase in chloride content is most reliable indicator of the first stages of salt-water intrusion into ground-water. A s rise in chloride may, however, be due simply to a temporary increase in the total concentra of dissolved salts and thus may be of no diagnostic significance. It is necessary to elimi the effects of changes in concentration by introducing a ratio between chloride and one or of the other ions in solution. For this purpose the ratio between chloride and bicarbonate total bound carbon dioxide) immediately suggests itself. Bicarbonate is usually the most abundant negative ion in ground-waters, while bicarbonate and carbonate taken together are present in virtually negligible amounts in sea water, the weight ratio of chloride to bicar being about 190 to 1. Even though, as has been pointed out, the bicarbonate content may be tered somewhat by the precipitation of calcium carbonate or by the oxidation of organic matt which accompanies sulphate reduction, there is such a large difference between the proporti of chloride and bicarbonate in normal ground-water and in ocean water that the ratio between these two ions is a useful index of the presence of sea water. A more serious difficulty is fact that other processes besides salt-water admixture can bring about a rise in the chlori bicarbonate ratio of ground-waters. The comparative analyses given by Stabler [10] of dese lakes and of the rivers which flow into them show that repeated evaporation and precipitati tend to raise the chloride-bicarbonate ratio, and indeed cause the composition of the lake- to change in many respect in the direction of sea water. Contamination by sewage and indus waters or by any relatively salty water of whatever origin will also cause an increase in chloride at the expense of bicarbonate. When an increase in the ratio between these ions t place in wells pumping from the bottom of an aquifer, however, where neither contamination saline wastes nor evaporation and precipitation are likely factors, then admixture of either cent or fossil sea-water may be inferred with some confidence.

Figure 2 shows the observed changes in chloride and bicarbonate content and in chloride bicarbonate ratio during the eight-year period from 1932 to 1940 in one of the municipal we of the city of Oceanside, California. The well was abandoned in 1940. Whether the very ev salt-water contamination shown in this well is due to admixture of recent or of fossil sea- is not known with certainty. Whatever the source of the salt water, if the warning given by increase in the ratio of chloride to bicarbonate had been heeded and pumping had been carri less intensively, the usefulness of the well might have been increased.

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s Institution of Oceanography,
niversity of California,
La Jolla, California

DISCUSSION

. C. LANE (Cambridge, Massachusetts)--I entirely agree that the problem is often an in-
al one, and would call attention to the help that may be given by petrographs on the chem-
nalysis of rocks. As I pointed out in my paper on calcium-chloride waters [comments and
m in Bull. Amer. Assoc. Petr. Geol.], manganese is one of the most easily precipitated of
and green chloritic secondary minerals are wide-spread. The problem of waters in Florida,
r from sea water or connate with the anhydrite deposits, is an illustration.

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SEXUAL PHASES IN WOOD-BORING MOLLUSKS

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SEXUAL PHASES IN WOOD-BORING MOLLUSKS

WESLEY R. COE

(From the Osborn Zoölogical Laboratory, Yale University, and the Scripps Institution of Oceanography, University of California) [1]

It has been demonstrated previously that the well-known shipworm *Teredo navalis* is typically protandric, nearly all individuals functioning as males when young and later changing to the female phase (Coe, 1936; Grave and Smith, 1936). Under favorable conditions the female phase may be followed by an additional sequence of male and female phases.

In no other species of the wood-boring mollusks (Teredinidae) is the sexual sequence fully known, although Yonge (1926) recognized protandry in *Teredo norvegica* and Siegerfoos (1908) concluded that it was present in "*Xylotrya gouldi*" = *Bankia fimbriata* (Jeffries).

During the past few years the writer has had the opportunity of investigating the biology of three species, *Teredo navalis, T. diegensis* and *Bankia setacea,* with particular reference to the development of the gonads and the sequence of the sexual phases. The results of this study may be briefly summarized and compared with previous reports on the sexuality of the shipworms.

SEXUAL PHASES OF TEREDO NAVALIS

This widely distributed species occurs on both the Atlantic and Pacific coasts of the United States and has been particularly destructive in past years in San Francisco Bay. Individuals in the female phase are larviparous, the fertilized eggs developing through about half the larval period in the maternal gill chambers. A free-swimming period follows the discharge of the larvae into the water. After settling upon a piece of wood, transformation to the adult condition takes place and boring into the wood begins (Kofoid and Miller, 1927; Grave, 1928).

The primary male phase becomes functional within four to six weeks after the completion of the free-swimming larval condition in the warmer season of the year or in warm localities, but may be delayed for six months or more under colder conditions. The body is then only 20 to 30 mm. in length and about 2 mm. in diameter. The female phase may begin at the age of eight to ten weeks.

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[1] Contributions from the Scripps Institution of Oceanography, No. 145.

Growth is rapid under favorable conditions. At the end of one year the body may have attained a length of 10 to 40 cm. and a diameter of 4 to 9 mm. In the meantime the individual has normally transformed to the female phase and has produced perhaps 1,000,000 young. A second sequence of male and female phases may have occurred.

Because of the long breeding season and the sequence of sexual phases, the proportion of the two sexes in each piece of wood will obviously depend upon the ages represented in the colony. In a recently attacked timber nearly every individual will be in the male phase. A few weeks later, after the sexual transformation has occurred, 60 to 90 per cent of the original colony will be functioning as females.

But in the meantime there may have been daily additions of recently arrived young from other pieces of wood, resulting in a continuing supply of male-phase individuals. These, together with the few so-called true males, and a small proportion of second male-phase individuals, are then available for the fertilization of the eggs produced by such individuals as are at that time functioning as females. Because of this overlapping of sexual phases all the older colonies are at all times represented by both sexual phases in varying proportions. Most of the smaller and consequently younger individuals will be functioning as males, while most of the larger, older individuals are in the female phase.

A rhythmical sequence of four sexual phases may be considered to represent the normal life cycle but this is seldom realized because of an earlier death due to parasites or to the exhaustion of the wood supply or to other unfavorable environmental conditions. Most individuals die after only two of these phases have been completed and many others survive only the primary male phase.

There are some variations in this sequence, however, because a second female phase may sometimes follow the first without an intervening male phase. Other individuals, known as true males, retain the male phase long after their contemporaries have changed to the female condition, and this may sometimes mean throughout their entire lifetimes.

Sexual Phases in Teredo diegensis

This species, like *T. navalis,* is protandric and larviparous, but the two species differ considerably both in the conditions of sexuality and in larval development.

T. diegensis Bartsch occurs abundantly and causes considerable damage along the coast of Southern California, and has been reported as far north as San Francisco (Kofoid and Miller, 1927). It is also found at the Hawaiian Islands. On the coast of Southern California this species breeds through all except the two or three cooler months of the year and through the entire year when the winter is warmer than usual. At the lower temperatures the larvae may remain within the maternal gill chambers for several months before they are discharged.

Ovulation occurs at intervals of a few weeks, the later broods of larvae often becoming established in the gills before an earlier brood has left. This condition occurs throughout the year. With the exception of young individuals and a few "true males" a sexually mature individual without a brood of larvae is seldom found.

Large individuals, 120 mm. or more in length, may have more than 1000 larvae in the gill chambers, while dwarfs may have less than 100. The bivalve larvae reach a shell length of 0.35 to 0.38 mm. before leaving the gills. In this species, as in *T. pedicellata* (Roch, 1940), the larvae remain within the gill chambers until nearly ready for metamorphosis. The free-swimming stage consequently lasts but a few hours if wood is available for attachment. The total period of larval development is about four weeks and is therefore of about the same length as in *T. navalis* (Coe, 1933*a*). In this latter species, however, only about two weeks of this time are spent in the maternal gill chambers, followed by a free-swimming period of about the same duration.

Shortly after being set free in the water the larvae of *T. diegensis* attach themselves to any available piece of wood but do not immediately penetrate the surface. Some of them may remain two weeks or more on the surface of the wood before beginning to bore. Their stomach contents show that minute particles of organic food materials are ingested in the meantime. Because there is no necessity for feeding during the brief free-swimming stage, this species may be reared from generation to generation in the aquarium. By supplying a fresh piece of wood occasionally the stock may be continued for at least several years. The aquarium water evidently contains sufficient materials to supplement the wood as sources of nourishment. After penetrating the wood the young teredos grow rapidly and reach the primary male phase within four to five weeks. The body is then about 8 to 12 mm. in length.

The primary gonad is composed of branching follicles filled with large, vacuolated cells and having a few proliferating germinal cells scattered along the walls of the follicles as shown for *Bankia setacea* (Fig. 1, *A*). This condition is closely similar to that described by Coe and Turner (1938) for the developing gonads of *Mya*. As the germinal cells increase in number they become differentiated into the two sexual types of gonia and then further differentiated into ovocytes and spermatocytes.

By their rapid proliferation and differentiation the spermatogenic cells encroach upon the spaces occupied by the vacuolated follicle cells and eventually fill the entire lumen of the follicle (Fig. 1, *B*). In some individuals the follicle cells contain numerous fragmenting and degenerating nuclei, representing a kind of atypical spermatogenesis, as described by Coe and Turner (1938) for *Mya*.

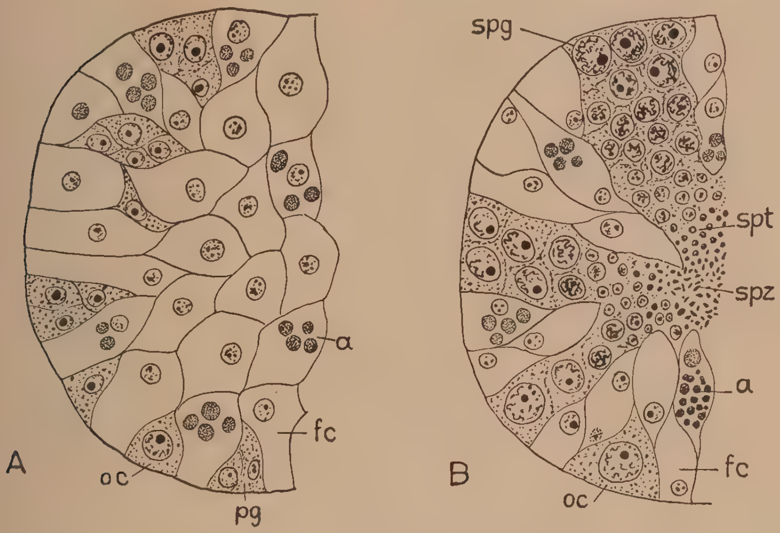

FIG. 1. *Bankia setacea.* Development of the primary ambisexual gonad. *A*, portion of section of young follicle, showing large vacuolated follicle cells (*fc*), with a few primary gonia (*pg*) and a single young ovocyte (*oc*) peripherally; several follicle cells contain atypical, degenerate nuclei (*a*), derived from original primary gonia. *B*, portion of follicle in early male phase, with a few remaining vacuolated follicle cells (*fc*) and various stages of spermatogenesis; *a*, atypical degenerate nuclei; *oc*, ovocyte; *spg*, spermatogonia; *spt*, spermatids; *spz*, spermatozoa.

There is considerable variation in the number and size of the ovocytes which are always present on the walls of the follicles during spermatogenesis. Some individuals, corresponding with the so-called true males of *T. navalis*, have only a few small ovocytes in each of the follicles (Fig. 3, *A*), while others show a preponderance of ovocytes in some or all of the follicles before the spermatozoa are fully ripe (Fig. 2).

Occasionally all the spermatozoa are discharged before ovulation occurs, resulting in a distinctly female phase (Fig. 3, *B*), but more frequently a functionally hermaphroditic condition is found. Both spermatozoa and ova may ripen at the same time and evidently both may be discharged simultaneously. Under experimental conditions self-fertilization occurs readily; this is followed by the formation of the polar bodies and cleavage, but only as far as the blastula and gastrula stages. For the normal processes of larval development the environmental conditions peculiar to the maternal gill chambers appear to be necessary.

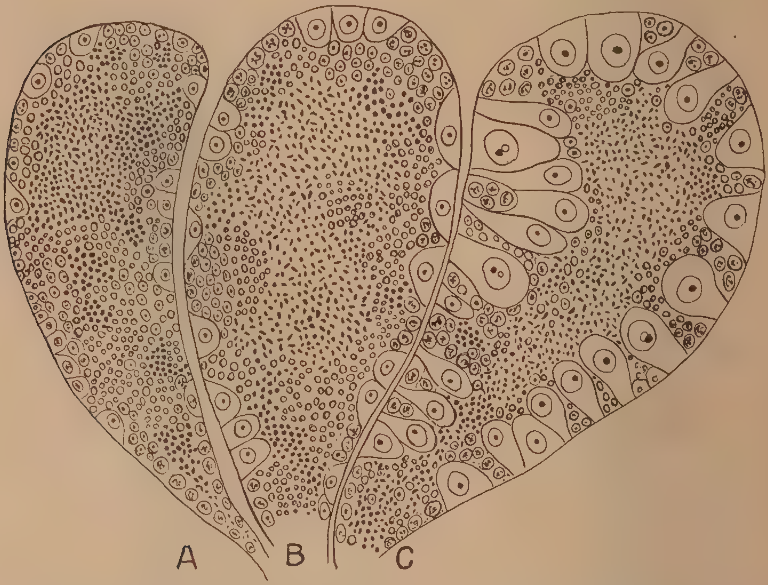

FIG. 2. *Teredo diegensis.* Sections of three follicles from gonad of second male-phase individual which had branchial brood pouches distended with larvae. *A,* immature follicle, principally in male phase, with relatively few ripe spermatozoa and with only small ovocytes in basal layer of germinal cells. *B,* more nearly mature follicle in male phase, distended with spermatogenic cells and many ripe spermatozoa; numerous half-grown ovocytes in basal layer of germinal cells. *C,* ripe follicle in hermaphroditic male phase; lumen filled with ripe spermatozoa and with nearly mature ovocytes densely crowded on periphery.

During some seasons this species becomes particularly injurious by boring in mooring ropes. A similar habit has been reported for *T. navalis* (Coe, 1933). Under such conditions only dwarf individuals are produced but many of these are nevertheless capable of forming a small number of ripe gametes. A single change of sexual phase, from male to female, may occur, although many individuals are killed by the disintegration of the rope before even the primary male phase is completed.

SEXUAL PHASES OF BANKIA SETACEA

This species differs from *Teredo diegensis,* with which it is often associated in the cooler waters on the coast of southern California, in being oviparous rather than larviparous. On reaching the female phase vast numbers of minute ova are produced and these are discharged directly into the water. Fertilization of these ova by sperm of other individuals takes place in the water. Then follows a free-swimming larval period of perhaps four weeks before the larva is ready to settle on a piece of wood and transform to the adult condition.

It is evident that all individuals pass through a functional male phase a few weeks after entering the wood. The two types of males are more easily distinguished than in either *Teredo navalis* or *T. diegensis.* About half of the young, male-phase individuals are apparently hermaphroditic; these complete spermatogenesis early and then change to the female phase. These are evidently genetically protandric females, while an approximately equal number retain the primary male phase much longer. The latter presumably represent the "true males" of other species (Coe, 1933*a*, 1936). Fully adult individuals, measuring 20 to 50 cm. in length, usually have the appearance of being either males or females, with little indication of ambisexuality. Only occasionally do their gonads reveal distinctly their essentially hermaphroditic nature. Careful examination of the gonad in full spermatogenesis, however, usually reveals a few ovocytes on the walls of the follicles and these may be considered as an indication that a change of sexuality may later occur. In the female phase likewise indifferent gonia show the potentiality of a sex change.

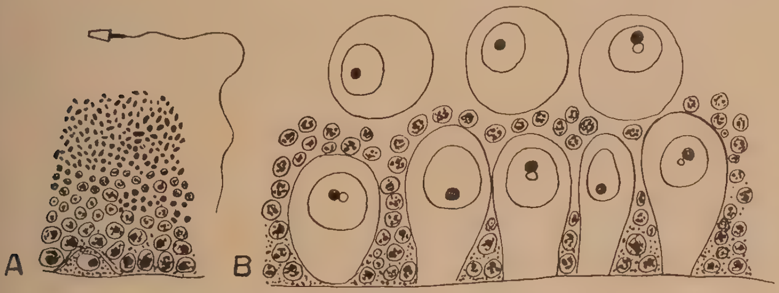

FIG. 3. *Teredo diegensis. A,* portion of gonad of young individual in "true male" phase, showing spermatogenesis and a single, more highly enlarged spermatozoön; a single ovocyte is shown at the base of the spermatogenic cells. *B,* portion of gonad in female phase, with ripe ova; those ova still attached to wall of follicle are surrounded by follicle cells with undifferentiated gonia basally.

The sexual conditions in this species are therefore similar to those of the oyster *Ostrea virginica* (Coe, 1938), which is seasonally of separate sexes but in which the sexual phase of any season cannot be predicted from the sexual condition of the preceding season. In *Bankia*, however, many of the females experience but a single change of sex, from male to female, while the true males may retain the male phase throughout life.

On the coast of southern California some individuals of *B. setacea* are found in spawning condition throughout the year. The majority of individuals, however, spawn only during the autumn and spring months, with resting periods in the winter and summer. Consequently wooden blocks and timbers become much more quickly and more heavily infested in the spring and autumn than at other times of the year.

Johnson and Miller (1935) found that settlement of this species in Puget Sound occurred principally from October to December and less abundantly from March to September. Kofoid and Miller (1927) also observed that in San Francisco Bay settlement of this species was confined to the cooler months of the year.

When removed from the body the eggs of *Bankia* develop rapidly to the free-swimming larval condition after artificial fertilization by sperm from another individual. The eggs of juvenile protandric females are sometimes capable of self-fertilization.

CONCLUSIONS

It is evident that the sexuality of these three species of pelecypods represents a graded series of ambisexual or hermaphroditic conditions intermediate between such dioecious forms as *Mya* or *Mytilus,* which are almost strictly of separate sexes, and those that are uniformly monoecious, as the larviparous oysters, *Ostrea edulis* or *O. lurida.* In all the dioecious pelecypods of which the sexuality has been extensively investigated hermaphroditism is found occasionally and this may include a large or only a small portion of the gonad.

Even the monoecious species usually have some dioecious tendencies, with some individuals ("true males") showing a preponderance of masculine characteristics, while others are more nearly feminine. A sequence of functional male and female phases is of common occurrence and in the case of long-lived species this may constitute an alternating rhythm. The wood-boring mollusks are of this type.

Protandry is characteristic of many species. This represents a juvenile type of sexuality and often occurs when the individual is very young and when the body has reached but a small fraction of its definitive size.

As mentioned above for *Bankia* and as Loosanoff (1937) found in *Venus,* the genetic females pass through a juvenile male phase before adult sexuality is realized. This has been reported for other species. In the oviparous oyster *Ostrea virginica* the proportion of the genetic females which pass through a functional male phase during their first breeding season depends both upon the particular local race concerned and upon the environmental conditions. This juvenile male phase is more frequently aborted or omitted under conditions favorable to rapid growth, thereby increasing the proportion of juvenile females. This species also shows a rhythmical tendency toward seasonal change of sex in later life (Coe, 1938).

In all the examples mentioned and in many others belonging to the various classes of mollusks, the sex-differentiating mechanism is so delicately balanced between the two sexual tendencies that relatively slight differences in environmental conditions may be potent in determining which of the two contrasted aspects of sexuality shall be realized. In some the entire population functions as male when young and as female when fully adult. An intervening functionally hermaphroditic phase may occur.

SUMMARY

1. The three species of wood-boring mollusks *Teredo navalis, T. diegensis* and *Bankia setacea,* are all protandric, with a strong tendency toward rhythmical changes of functional male and female phases.

2. Each species differs as to the degree of ambisexuality characteristic of the primary male phase and of the subsequent sexual phases.

3. The primary gonad in all three species develops from branching follicles filled with large vacuolated follicle cells and having the primary gonia scattered along walls of the follicles.

4. In each of these species the gonads of young animals indicate that there are two types of primary male-phase individuals: (1) ambisexual males or protandric females, characterized by many ovocytes on the walls of the spermatic follicles, and (2) true males with few ovocytes. In those of the former type the male phase is of short duration, while true males retain the male phase longer or in some cases indefinitely.

5. In *T. navalis* the first female phase does not usually become functional until nearly all the sperm of the primary male phase have been discharged. Functional hermaphroditism is not usual, although the gonad is histologically ambisexual during the change of sexual phase in both directions.

6. In *T. diegensis,* on the other hand, functional hermaphroditism is of usual occurrence and the sexual phases are not sharply demarcated.

7. In *B. setacea* functional hermaphroditism occurs only occasionally in the primary male phase; the subsequent sexual phases are clearly differentiated, often with a resting stage intervening between two sexual phases. The sexual phases are of the alternative type in that any sexual phase, after the first, may be followed by either a male or female phase if the length of life suffices. The relatively short life of many individuals, however, allows but a single change of sex, from male to female, in the genetic females, and none at all in true males.

8. In all of the three species the eggs begin development after artificial fertilization. In *Bankia* the larvae may be reared to the free-swimming veliger stage, but in the other two species the larval stages require the peculiar environmental conditions of the maternal gill chambers. Under experimental conditions self-fertilization and apparently normal cleavage occurs readily in the two species of *Teredo* and occasionally in *Bankia*.

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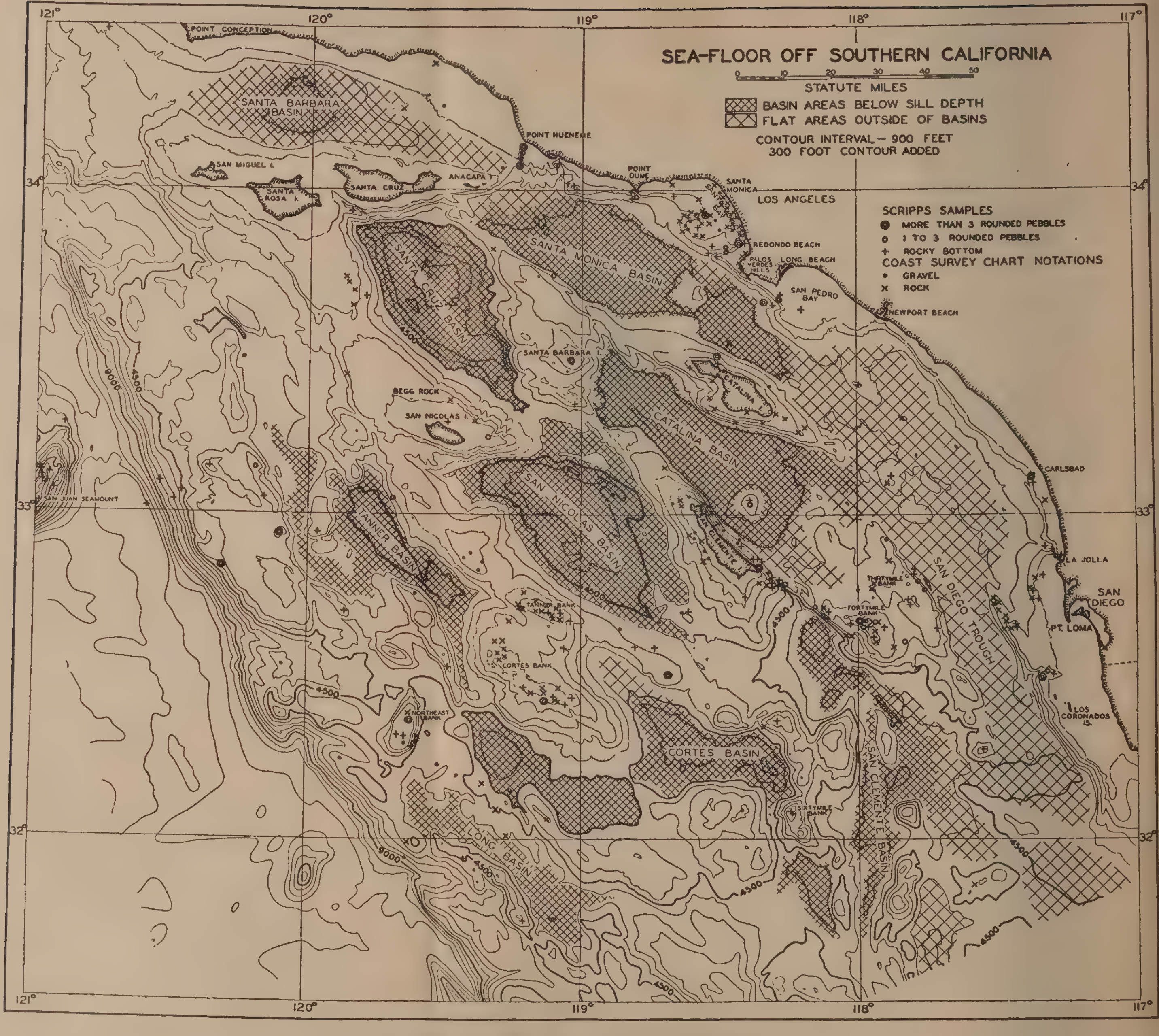
Contribution No. 146


SEA-FLOOR OFF SOUTHERN CALIFORNIA
0 10 20 30 40 50
STATUTE MILES
BASIN AREAS BELOW SILL DEPTH
FLAT AREAS OUTSIDE OF BASINS
CONTOUR INTERVAL – 900 FEET
300 FOOT CONTOUR ADDED
SCRIPPS SAMPLES
MORE THAN 3 ROUNDED PEBBLES
1 TO 3 ROUNDED PEBBLES
ROCKY BOTTOM
COAST SURVEY CHART NOTATIONS
GRAVEL
ROCK
121°
120°
119°
118°
117°
34°
33°
32°
POINT CONCEPTION
SANTA BARBARA BASIN
POINT HUENEME
SAN MIGUEL I.
SANTA ROSA I.
SANTA CRUZ
ANACAPA
POINT DUME
SANTA MONICA
LOS ANGELES
SANTA MONICA BAY
REDONDO BEACH
PALOS VERDES HILLS
LONG BEACH
SAN PEDRO BAY
NEWPORT BEACH
SANTA CRUZ BASIN
SANTA MONICA BASIN
SANTA BARBARA I.
BEGG ROCK
SAN NICOLAS I.
CATALINA
CATALINA BASIN
SAN NICOLAS BASIN
SAN CLEMENTE
TANNER BASIN
TANNER BANK
CORTES BANK
NORTHEAST BANK
CORTES BASIN
LONG BASIN
SAN CLEMENTE BASIN
SIXTYMILE BANK
THIRTYMILE BANK
FORTYMILE BANK
SAN DIEGO TROUGH
CARLSBAD
LA JOLLA
SAN DIEGO
PT. LOMA
LOS CORONADOS IS.
SAN JUAN SEAMOUNT
4500
9000

SEA FLOOR OFF SOUTHERN CALIFORNIA

Showing the topographic environments in which rock bottom and gravel bottom were found by dredging from scientific vessels or were reported by the U. S. Coast and Geodetic Survey. Note that the various symbols give some indication of the significance of the samples. The data are not entirely complete in the near-shore zones of the continental shelf and are somewhat generalized in places where crowding was necessary. The contours are taken from Shepard and Emery (1941, Chart I).

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NONDEPOSITIONAL PHYSIOGRAPHIC ENVIRONMENTS OFF THE CALIFORNIA COAST

BY FRANCIS P. SHEPARD

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ILLUSTRATIONS

Facing page
Sea floor off southern California ... 1869
Rock dredge, wave-cut terrace, and rock samples ... 1872

ABSTRACT

ecent explorations on the Scripps Institution vessel have confirmed the impression ained from previous work that there are extensive areas off the California Coast re deposition is either very slow or nonexistent. Dredging and coring operations w either rock bottom or a very thin sediment cover on most of the deep banks off thern California, on many steep submarine slopes, on the walls and even on the rs of submarine canyons, and on the outer portions of the continental shelves.

Depth seems to have little bearing on these occurrences. Further possible evidenc of absence of important deposition comes from the finding of sand and gravel in ver deep portions of submarine canyons where mud should be the chief sediment. San was discovered even in portions of the troughs and basins off southern California a depths ranging around half a mile. This sand may be significant because the chie sediment being supplied to the deep areas at present, insofar as can be determined is silt and clay. The importance of bottom currents and of submarine mud flows i preventing deposition is discussed.

INTRODUCTION

The idea still seems to prevail that deposition of sediment is takin place over the greater part of the sea floor bordering the continents. However, a recent symposium (Trask, 1939) brought together considerabl evidence from the continental shelves in various parts of the world suggesting that deposition is by no means universal. During 1938 investigation on the *E. W. Scripps* greatly extended earlier information (Revelle an Shepard, 1939) concerning sedimentation conditions off the Californi coast. The area off southern California, where most of the work wa accomplished, proved a particularly fitting place to look for nondepositional marine surfaces because it represents so many different environments. They include narrow continental shelves and insular shelves relatively deep basins and troughs; banks and "seamounts"[1] with summi depths varying from a few feet down to 2 miles below sea level; escarpments with slopes up to 100 per cent; and submarine canyons.

Extensive dredging and coring of the bottom in this southern area hav suggested that of all the different environments only the basins, troughs and slope bases are receiving appreciable quantity of sediment unde present conditions. There is even evidence that finer sediment by-passe portions of the inner basins and troughs. Investigations off central an northern California, partly of earlier date, have also indicated the absenc of sediment accumulation over an extensive area. The evidence for thi nondeposition, and the possible underlying causes are discussed in th present article.

ACKNOWLEDGMENTS

The work on which this report is based was made possible largel through a grant from the Penrose Bequest of the Geological Society c America and through the active co-operation of staff members of th Scripps Institution of Oceanography. The California Fish and Gam Commission and the U. S. Coast and Geodetic Survey also provided opportunities for dredging operations by the writer. The co-operation of Roge Revelle, K. O. Emery, and Robert Dietz was of high value. The write

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[1] The term "seamount" was introduced by the U. S. Coast and Geodetic Survey to designate mountain mass rising above the deep sea floor and is used here in contrast to "banks" which rise abo a shelf or zone of intermediate depth.

shes to express sincere appreciation to these individuals and organiza- ons.

EVIDENCE OF NONDEPOSITION

ROCK BOTTOM

Of the various lines of evidence suggesting nondeposition of sediments e most significant is, of course, the discovery of rock bottom. Reports of is type of bottom have come from numerous localities off the California ast (Pl. 1). These reports were chiefly obtained by sounding operations the U. S. Coast and Geodetic Survey. The finding of fresh scratches on e sounding lead is one basis for Survey reports of "Rocky". Such ratches suggest the presence of rock bottom since the lead must have me in contact with some hard firm substance. Gravel could not produce ch markings although large boulders could scratch the lead, so that the istence of ledge rock is not proven by such findings. However, absence marine deposition, except in the littoral zone, is indicated by a bouldery ttom as well as by ledge rock. The other basis for the report of rock ttom by the U. S. Coast and Geodetic Survey is the finding of angular ck fragments in the tallow cup at the base of the sounding lead or in e jaws of the small telegraph snapper which is sometimes used. The esence of these rock fragments does not prove the absence of deposition nce stray pieces of rock are introduced into an area by various flotation ethods. In some areas which are free from any other appreciable source sediments and where the currents are favorable, small rocks dropped om kelp may become an important factor.

The dredging operations by the writer have produced more definite evi- ence of rock bottom. Dredges, such as shown in Figure 1 of Plate 2, were ed. Numerous rock fragments were recovered, many so large that ance introduction by kelp would be improbable (Pl. 2, fig. 3). The rocks edged from slopes may be talus or slide rocks derived from a higher sition. However, the large fragments from the tops of banks or from flat elves were probably *in situ*, and some of the fragments from slopes were early ledge rock since they showed fresh fractures. A further indication ledge rock was the firmness of the rock masses on the bottom. Fre- ently the dredge caught on bottom hard enough to stop the progress of e vessel. Great difficulty was encountered in breaking off fragments, d several dredges were lost in the attempt.

Finally, the existence of kelp off a coast is an almost certain indication rock bottom. This marine plant grows only where there are rocks of fficient size for the holdfasts to take root. Insofar as the writer knows, e kelp beds on the California coast are found on ledge rock where little diment exists.

GRAVEL BOTTOM

Streams that enter the ocean with high velocity may introduce gravel, or waves working on cliffs containing the proper type of rock to form gravel may develop a potential marine conglomerate. However, investigations by the writer along the California coast seem to indicate that this gravel is kept in the zone of violent wave action near the coast and under storm conditions is normally piled high on the shore. Evidence compiled by Johnson (1919, p. 93-94) showed that rock ballast dumped miles out from land is sometimes carried shoreward. Accordingly, the discovery of gravel deposits on the shelf many miles from shore or in other areas still more remote from sources suggests that deposition is not taking place where the gravel is found.

Even if unusual wave conditions do allow the movement of gravel to the outer portion of the shelves, transportation to the outlying banks off southern California is impossible. The gravel obtained from many of these banks (Pl. 1) indicates the absence of appreciable deposition. Had the gravel been introduced by kelp, accumulation of other sediment at any appreciable rate would mask the occasionally introduced pebbles.

SANDY BOTTOM IN DEEP WATER

Layers of clean sand have been found in some of the basins off southern California where the predominant sediment introduced from the land is of much finer grade (Revelle and Shepard, 1939, p. 279). The following three possible explanations for this sand can be offered: (1) that deposition is not taking place and that the sand is residual; (2) that the fine sediments are kept in suspension allowing accumulation of only the coarser fractions; and (3) that attrition due to currents causes the concentration of the sandy portion of the sediment in some portions of the basins.

The existence of coarse sand on the outer edge of the continental shelves may be an indication of nondeposition, particularly if finer sediment is found nearer shore. In connection with his work off the Atlantic Coast Stetson (1938, p. 40) found that "the well sorted sands at the break in slope are probably residual from Pleistocene conditions. . . ." The present writer and his collaborators have produced evidence for the same view in sedimentation studies off both the east and west coasts (Shepard and Cohee, 1936, p. 455; Shepard and MacDonald, 1938, p. 213).

TOPOGRAPHIC INDICATIONS

Where deltas are built out into fiords or lakes with steep margins it is possible for foreset slopes to develop with a declivity up to about 40 degrees (Twenhofel, 1932, p. 604). This, however, is very exceptional

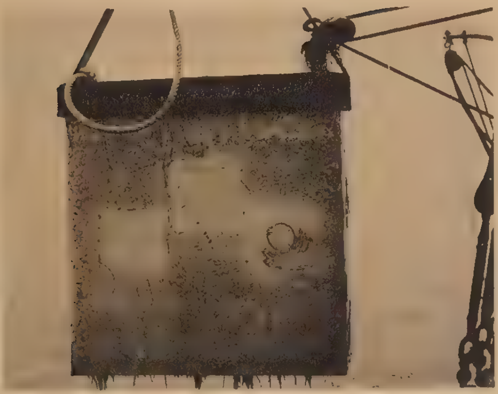

FIGURE 1. ONE OF THE TYPES OF DREDGES
Used to obtain rock from the sea floor off the California coast.

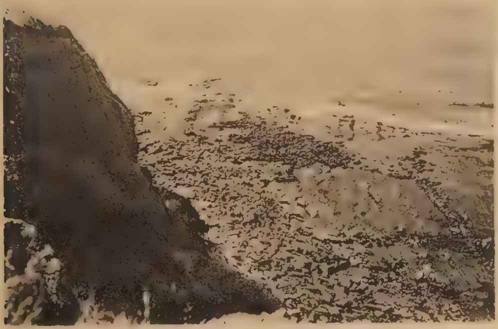

FIGURE 2. WAVE-CUT TERRACE
Exposed at low tide off La Jolla, California.

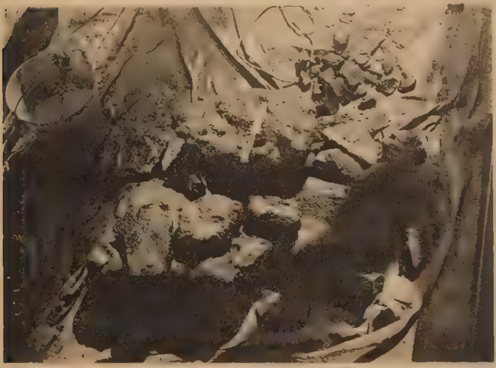

FIGURE 3. ROCKS OBTAINED IN A DREDGING OFF SOUTHERN CALIFORNIA
In water 3600 feet deep. Note the combination of large angular blocks of shale and rounded pebbles and cobbles of igneous rock.

ROCK DREDGE, WAVE-CUT TERRACE, AND ROCK SAMPLES

and ordinary marine deposition slopes are much gentler. According to charts the slopes in front of large deltas on the shelf average only 0.7 per cent. The continental slopes are much steeper than this. The writer constructed 500 profiles off all shores of the world. The average slope of the steepest portions of each of these profiles is 8.6 per cent. The slopes appear to have been flattened where they have been built forward by deposition from large rivers. For example the continental slope outside the passes of the Mississippi Delta has an inclination of only 1.0 per cent. Therefore, steep submarine slopes, except in a coral reef area, indicate that they are not due primarily to outgrowth of sediments from the land, although they may be somewhat masked by sediments. Furthermore, if the slopes are located in places with no available source of clastic sediments, they would likely be nondepositional surfaces.

Where marine slopes are straight as well as steep, it seems highly probable that they have not been greatly affected by deposition. The forward building of a slope should result in bulges where active deposition occurs. Similarly the sharp V-shape of submarine canyons and of a few submarine fault valleys suggests the absence of any great amount of fill subsequent to their development.

NONDEPOSITION ON CONTINENTAL AND INSULAR SHELVES

GENERAL CONSIDERATIONS

The term continental shelf here refers to shallow-water platforms,—less than 100 fathoms deep—which lie adjacent to the land; the definition does not include the Basin and Range topography of the greater part of the area shown in Plate 1. Similarly, insular shelves refer to the shallow-water platforms around the islands. Numerous bottom indications from almost all parts of these shelves have been obtained by the U. S. Coast and Geodetic Survey. While information from this source is fairly extensive, the writer's dredging operations on the shelf were not so numerous as in some other environments. However, dredging was undertaken on portions of the shelves off San Diego, off Long Beach, in Santa Monica Bay, off Point Sur, in Monterey Bay, and off Punta Gorda. The insular shelf off Catalina Island was dredged in many places. Further information came from the finding that canyons which cut into the shelves are commonly rock-walled.

ROCKY ZONES NEAR SHORE

The California coast can be divided into three distinct types: (1) cliffed coasts where the waves have eaten into the rocks of the headlands or mountain ranges terminating at the shore; (2) cliffed coasts where the sea has cut into recent unconsolidated deposits and has in general developed a straight shore line; and (3) lowland coasts where the sea comes into contact with a coastal plain or delta. Rocky bottom is almost invariably found directly off the first of these types. On the other hand, off the second type of coast the near-shore zones[2] rarely have rock, and no cases are known off the third type.

The near-shore rocky zones are visible in many places at low tide (Pl. 2, fig. 2). Elsewhere when the sea is calm and the water clear the rocks may be discerned from the tops of the cliffs. In many places isolated stacks rise above the surface. The presence of kelp, which is thought to grow only on rocky surfaces, also indicates bare rock. Kelp grows around or adjacent to almost all the rocky headlands along the California coast, such as Point Loma, Point La Jolla, the Palos Verdes Hills, Point Dume, Point Sur, Point Lobos, Monterey Peninsula, and Cape Mendocino. These zones of rocky bottom can be traced on charts, either by kelp or bottom notations, out to depths of 60 to 120 feet and for distances of 1 or 2 miles from the shore. In places even greater depths and distances are found. Various maps of bottom character show the approximate size of these rocky areas (Revelle and Shepard, 1939, Fig. 1; Shepard and MacDonald, 1938, Fig. 2; Shepard and Wrath, 1937, Fig. 1). However, these zones are not devoid of sediment; actually patches of sand are scattered over the rock surface. This sand is probably of transitory character rather than a permanent sediment accumulation.

SHELF MARGINS

The near-shore rock surfaces, previously discussed are examples of wave-cut terraces. However, the zone at or near the outer margin of the continental shelves, having abundant evidence of nondeposition, does not conform with the theoretical concept of wave-built terraces, commonly assumed to have formed the outer shelves. There are reports from many parts of the world of either coarse sediment or of rocky bottom both at and near the outer margin of the shelf (Shepard, 1932, p. 1038; 1939, p. 223) so that the evidence to be presented is not unique for the California coast.

The rocky outer zones of the shelves are reported by the U. S. Coast and Geodetic Survey off all of the types of California coast, even to a limited extent off the lowlands, as for example, on the shelf off the alluvial plain south of Los Angeles. The authenticity of some of these rocky zones was established by dredging operations on the *E. W. Scripps.* Large slabs of rock were obtained from the outer shelf off Long Beach, in Santa Monica Bay, off the western edge of the Santa Monica Mounains, off Point Sur, and in Monterey Bay. Most of this material is learly of local derivation.

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[2] Meaning roughly zones within a half mile of the shore line.

Coarsening of sediment at the edge of the shelf was observed in part of Santa Monica Bay (Shepard and MacDonald, 1938, Fig. 3b) and Monterey Bay (Galliher, 1932, Pl. 3). To this evidence may be added many U. S. Coast and Geodetic Survey reports of gravel and coarse sand along the outer shelves. In collecting samples around Catalina Island the writer found a coarsening of sediment at the break in slope n numerous places both on the exposed and semiprotected sides of the island (Shepard and Wrath, 1937, p. 43). Off Avalon Cove where quiet waters prevail most of the year coarsening at the break in slope was shown by the selective sorting of calcareous shells, largely Foraminifera, which cover this insular shelf. On the exposed side of the island dominantly clastic sediments also showed a distinct coarsening at the edge. Furthermore, the U. S. Coast and Geodetic Survey found rock bottom in a considerable number of places along the shelf margin.

BARE WALLS AND FLOORS OF SUBMARINE CANYONS

The nature of the walls and floors of the submarine canyons is discussed at length elsewhere (Shepard and Emery, 1941, p. 86-89) so that only partial consideration need be given here. A total of 21 canyons along the California coast have now been dredged, and rock has been discovered in all but four. While much of this rock was of relatively soft Tertiary sedimentary material, it serves to show that recent sediments are not covering the canyon walls. On the other hand, most dredging on the walls netted considerable quantities of mud and sand. These sediments were even found on walls having a 50 per cent slope. This combination of bare rock and sediment seems to indicate that the sediment does not accumulate permanently, but is lodged there until it acquires sufficient weight to start a slide or mud flow down into the canyon bottom. Otherwise, in the long interval which appears to have intervened since the canyons were submerged (Shepard and Emery, 1941, p. 126-128) sediment should have cloaked the walls quite completely. Dredging results seem to indicate that more rock is exposed on these walls than on the walls of typical land canyons on the adjacent coast.

Preliminary examination of the California canyon floors gave the impression that most of them were receiving sediment (Cohee, 1938). However, more complete study with improved equipment showed that only those canyons which head at some distance from the coast contain appreciable fill. The muddy floor sediment of those canyons which extend in close to the coast was found to consist of only a thin cover. For example coring with the Emery-Dietz device along the axis of

Monterey submarine canyon established the absence of any appreciable mud fill from the head out to depths of 5000 feet. The bottom was hard-packed sand, gravel, or rock. Dredging brought up several types of rock from the floor of this canyon. Numerous tests in other canyons heading near the coast showed conditions similar to those in Monterey Canyon. On the other hand those canyons terminating landward at some distance from the coast were found to have at least a 10-foot fill of mud. Whether or not this discovery shows that the outer canyons are being gradually filled remains undecided. However, the evidence obtained by Stetson (1936, p. 356) from the east coast canyons suggests continuous fill at least since the Wisconsin glacial epoch. On the other hand the general V-shape, indicated by soundings in the canyon heads, suggests that deposition has not produced any great fill even in those canyons which lie at a considerable distance from the coast. Furthermore, the 3 feet of postglacial fill in the canyons off the New England coast (Stetson, 1936, Table 1 and p. 356) shows that a very considerable period would be required in order to greatly modify the V of the canyons.

The flat bottom found in some of the canyons off the California coast is no proof that there has been recent deposition. Monterey Canyon was found to have a floor half a mile across in depths of 5000 feet, but a core taken near this carefully measured section showed only a thin film of mud over sand which graded down into gravel containing pebbles 5 centimeters in diameter. Along with this coarse clastic debris, numerous shell fragments were found. The abundant shells and gravel seem to prove that the material is residual from a time when the canyon stood much higher in relation to sea level. Thus unless there has been a catastrophic submergence in recent times the narrow valley flat has been kept clean of sediment for a very considerable period.

BARE SLOPES OF SUBMARINE ESCARPMENTS

The various escarpments off the coast of southern California, illustrated by the contours in Plate 1 (*see also* Shepard and Emery, 1941, Chart I) are so steep that it is natural to expect that sediment would only lodge on them temporarily. Notations concerning the bottom on these slopes obtained by the U. S. Coast and Geodetic Survey are not very numerous but they do show a large percentage of rocky bottom. A notable place for such observations is on the escarpments bordering the basin between Catalina and San Clemente islands. The writer has also dredged a number of these escarpments bringing up considerable quantities of rock, although some places failed to produce any rock.

In the light of present knowledge, at least the steep upper portions of these escarpments, which are thought to be fault scarps (Shepard and

mery, 1941, p. 71), should be considered as probable nondepositional
urfaces but the evidence is not yet conclusive. In this connection the
ork of Kuenen in the Dutch East Indies should be considered. Coring
y Kuenen (1934, p. 70) on slopes up to 34 degrees failed to produce any
ppreciable quantity of rock. However, since most of the cores were
ss than 1 meter in length, it is always possible that the submarine slopes
ere covered with a thin veneer of sediment which would have been
ierced if longer cores had been obtained. Furthermore, dredging opera-
ions because of the greater area covered have far greater chance of
ncountering rock outcrops.

ROCKY BANKS AND SEAMOUNTS

Off the coast of southern California there are a total of 77 submarine
minences rising over 1000 feet above their surroundings. The largest
f these, which has been called San Juan Seamount, rises approximately
0,000 feet above the abyssal depths which surround it. Most of the
thers, however, have much less relief and rise above the "continental
orderland"[3] where the bottom is at a level more closely allied to that
f the continent than to the deep ocean floor. Most of these masses are
eferred to as banks and have rather flat tops. The summits of these
ubmarine mountains are extremely variable in elevation. On the con-
inental borderland the banks vary from depths of a few feet down to
bout 4500 feet. On the deep-sea floor the seamounts have summit depths
rom 1800 feet down to 11,400 feet.

The bottom character of many of the banks was determined by the
J. S. Coast and Geodetic Survey. The writer dredged 14 of the banks
ff southern California as well as San Juan Seamount. As a result, infor-
nation from most of these features is available. There seems to be
ittle doubt that most of the elevations, at least off this coast, are swept
ree from mud. Sand, consisting of Foraminifera and other calcareous
rganisms, masks portions of many of the banks which have depths
f less than 600 feet, but the banks in general were found to have
are-rock surfaces, and even the shoaler banks have some outcroppings
f rock. The dredge generally caught on ledge rock while being pulled
cross one of these submarine banks. On only one elevation did the
redge encounter mud and fail to give any signs of hitting rock bottom.

The rocky bottom is not confined to the tops of banks and seamounts.
n several cases where dredging failed to break loose any rock on the
ummit of a submerged mountain, the dredge was pulled up the moun-

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[3] "Continental borderland" is a term applied to the sea floor off the southern California coast and
ff adjacent portions of Lower California where the topography is of the Basin and Range character
ound on the adjacent lands.

tainside, and rock was encountered 1000 feet or more below the summit. Rock was recovered from the east wall of San Juan Seamount at a depth of 5000 feet, and a small dredge was wedged so securely in the rock on the northwest side at 9000 feet that it could not be dislodged. An attempt to secure a core at 9750 feet on the north side resulted in a badly bent nose and tube. Here, also, rock must have been encountered or at least a hard bottom free from recent sediments.

Even more surprising was the indication of nondeposition on the deep-sea floor at 11,800 feet about 300 miles southwest of the coast of southern California. An attempt was made to obtain a core in this area, where the depth is 2000 feet less than that existing about 60 miles distant on either side. A bent tube and bent core nose showed that the core barrel hit a hard bottom at the 11,800-foot depth. Fragments of manganese oxide were recovered stuck inside the valve, and a trace of red clay adhered to the core barrel. On the other hand in the deeper water to the north and south the core barrel penetrated about 11 feet into red clay. These findings suggest that even the elevations which rise slightly above the deep ocean floor might be negative sedimentation areas.

Not as much is known regarding the banks and seamounts off central and northern California. The U. S. Coast and Geodetic Survey sheets indicate rocky bottoms on some small banks. Large fragments of rock were also obtained by the writer from one bank off Point Sur. At a depth of 5800 feet near the summit of Davidson Seamount (Shepard and Emery, 1941, Chart II) the U. S. Coast and Geodetic Survey indicate rocky bottom.

The nature of the rock obtained from these various submarine hills will be discussed fully in a succeeding paper by Emery and the writer. The rocks are of considerable variety but consist more commonly of either andesite or phosphorite than of other types. However, a considerable amount of shale, limestone, and sandstone was discovered. The presence of phosphorite on so many of these banks indicates long continued absence of deposition, since phosphorite is found in the stratigraphic column in association with nondepositional surfaces. The significance of the phosphorite will be discussed elsewhere in a paper by Dietz, Emery, and the writer.

FORAMINIFERAL AND GLAUCONITIC SANDS OF SUBMARINE SADDLES

Several saddles between ridges and banks have been sampled (Revelle and Shepard, 1939, p. 257). In each case cores were obtained consisting of foraminiferal shells or glauconitic sand. Despite the thousands of feet of water which cover these saddles, mud was very scarce in the

res. Also, in several cases rock fragments were found both at the
rface and down in the sand.

It cannot be ascertained that there is no deposition on these saddles,
t the presence of glauconite suggests a very slow rate of deposition
ladding, 1932, p. 79-82; Galliher, 1935, p. 1362-1363). Also, the finding
foraminiferal sand rather than mud, which is found in the adjacent
sins, shows that the finer particles are not accumulating on the saddles.
ie origin of the rock fragments is difficult to ascertain. Since they
e of small size, the possibility of introduction by kelp should be con-
lered.

SAND DEPOSITS OF INNER BASINS AND TROUGHS

The trough off San Diego with depths around 3500 feet and the rela-
vely shallow basins off Palos Verdes Hills and outside Santa Monica
ay, where the water attains 2950 and 3100 feet, respectively, have been
und by Revelle and the writer to contain extensive areas where rela-
vely clean sand underlies a small thickness of mud or is even found
the surface. For the most part the coring device did not penetrate
rough the sand, so that its thickness is unknown. However, in other
isins thin sand layers have been discovered interbedded with muds,
that it seems likely that no great thickness is represented by the sand
ne in these near-shore basins and troughs off southern California.

The relatively clean sand in these deep environments can be inter-
eted in the three ways mentioned previously. If the sands constitute
normal basin and trough deposit, there must be periods during which
rge quantities of sand are carried out into the basins, making layers
hich may be even a foot or more in thickness. These periods must
assumed to accompany unusually great waves. However, it is hard
understand why the dominant sediment washed out to these depths
such times is sand. During typical storms along the southern Cali-
rnia coast great quantities of mud are introduced into the sea and
rried far out from the land (Revelle and Shepard, 1939, p. 271-274).
lso, the sand moved seaward during storms is found to accumulate in
iallow water within 1000 or at least 2000 feet of the shore (Shepard
id La Fond, 1940).

If, on the other hand, current conditions exist within portions of the
isins which prevent the deposition of fine sediments, allowing only the
ccasionally introduced sand grains to accumulate, a condition close to
iat of nondeposition is attained. The third possibility that the currents
ave locally reworked normal basin sediments causing a residual concen-
ation of sand grains by attrition represents a type of nondeposition
lthough the fact that the sand occurs in layers shows that nondeposi-

tion is not a lasting state. The finding of thick accumulations of muddy sediments lacking sand layers in other portions of the same basins and troughs supports either of these last two possibilities.

POSSIBLE CAUSES OF NONDEPOSITION

ADEQUACY OF SEDIMENT SUPPLY

Nondeposition could of course result from absence of supply of sediment to an area. The available evidence for the area off California, however, as has been shown previously by Revelle and Shepard (1939, p. 268-278) suggests that sediments are both introduced in large quantities into the ocean off this coast and are carried seaward for long distances. The introduction of mud into the ocean during floods is made evident by the brown color of the water extending for many miles seaward from the river mouths. This mud moves seaward largely near the surface. Probably considerable mud also moves seaward along the bottom and perhaps to some extent at intermediate depths.

The cause of sand transportation out into deep water is one concerning which few data are available. The samples appear to indicate that such transportation does take place, but observations of sand movements along the piers show that during normal winter storms most of the sand is carried out only for a few hundred feet where it lodges and is carried in again during the calm weather of the following summer (Shepard and La Fond, 1940, p. 275). Work by the Los Angeles engineering department also shows that sand is shifted seaward for a short distance in winter and returns to the beaches in summer. Possibly extreme conditions such as have not been recorded in recent years would be necessary for the seaward transportation of the sand into the basins and troughs.

EFFECTS OF WAVES

Few quantitative data are available to show whether waves can be of importance in keeping sediment from accumulating in most of the environments which have been discussed. Previous information regarding sand movements has suggested that waves do not have much cutting effect except very near the shore. On the other hand Kuenen (1939), in discussing the nondepositional surfaces at the breaks in slope on the outer edge of the continental shelf, presented evidence obtained by Vening Meinesz that submarines are considerably moved by waves at depths of 60 meters during rough weather, and he also showed how waves approaching the continental shelf have their energy concentrated near the break in slope and for an indefinite distance in along the shelf. Kuenen suggested that this factor accounts for the coarse sediment which Stetson ıd the present writer had reported from the edge of the continental ıelves.

POSSIBLE EFFECTS OF TSUNAMIS

Tsunamis (tidal waves) of large dimensions are unknown along the alifornia coast, but such waves may have occurred prior to the arrival civilized man in this region. The seismicity of the area suggests this ›ssibility. If Kuenen is correct in attributing some stirring action to dinary waves at the edge of the shelf, the effect of tsunamis must be ır greater.[4] Tsunamis have excessively long wave lengths and there-re little decrease in velocity toward the bottom. It even seems possible ıat large tsunamis may have had important effects on the deep outer ınks where their force would be concentrated due to the abrupt rise om greater depths.

Tsunamis may have played a very important part in keeping the ınks and breaks in slope at the outside of the shelves free from sedi-entary accumulation. These waves may have served as the means of ırrying sand out into the basins and troughs and thus account for the ınd deposits previously considered. The tsunamis would, of course, ·ing out large quantities of fine sediment, but violent stirring action ıay have prevented the deposition of the finer sediment along with the ınd.

On the other hand tsunamis should not be given too much weight ırtly because the character and effect of their movement are still mat-ırs of uncertainty but mainly because there is no evidence that they have ·er occurred off the California coast.

TIDAL CURRENTS

The nature of tidal currents is such that their velocity is increased ; a break in slope or on any rise above the general level of the ocean ›or. A recent study by Fleming (1938, p. 196-201, Fig. 75) illustrates ıis increase of current at the edge of the continental shelf in the Gulf Panama. On the other hand the information now available on bottom ırrents off the California coast (Shepard, Revelle, and Dietz, 1939; evelle and Shepard, 1939) gives little information which suggests that ıe tides play an important part in producing these nondepositional sur-ıces. Important tidal components to the currents were revealed in only vo localities, and even there it could not be ascertained that the tide as the chief motivating force of the current. The absence of large tidal ›mponents becomes all the more significant since periods of spring tides ere chosen for the investigations whenever possible. However, neither ıelf margins nor small isolated banks where tides might play a particularly great role have been investigated, and this may account for the lack of discovery of significant tidal currents.

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[4] Bucher (1940) recently suggested tsunamis as a cause of submarine canyons.

NONTIDAL CURRENTS

The investigation of the bottom currents has revealed the presence of internal waves and of large moving eddies with vertical axes (to be described in a future article by Revelle and Shepard). Observations have been made along the bottom of submarine canyons, in the bottom of deep basins, on submarine escarpments, on open shelves, and on submarine ridges. The data come from depths of a few feet to 6000 feet. Detectable currents were recorded in all localities investigated except on Cortes Bank where an attempt to measure currents in 100 feet of water failed, due apparently to the strong wave motion on the bottom which wrapped the current meter around the tripod from which it was suspended. The use of this tripod allowed the measurement of the currents to be made directly on the bottom eliminating any interference from the motion of the ship.

In practically all localities regardless of depth the currents attained sufficient velocities to be capable of transporting fine material, and in some places currents were found which according to the work of Hjulström (1939, Fig. 1) should be strong enough to roll gravel along the bottom. However, there are considerable lapses in current movements which might allow all but the silt and clay to settle, and thus greater velocity would be required to set the particles again in motion. The higher velocities, with a maximum of 36 centimeters per second, would, according to Hjulström, have carried back into suspension sand particles (.05 to 2.0 mm.) but would not have disturbed silt-clay aggregates or gravel. However, as yet there are few data to prove whether the observations regarding stream transportation and erosion to which Hjulström refers, are also applicable to the ocean floor. Assuming the Hjulström values to be approximately correct, the currents which we have measured give a satisfactory explanation of the by-passing of the sediments over the nondepositional surfaces. The clean sand layers found in the basins may be due to the existing currents.

On the other hand there are some reasons to question the importance of the currents in keeping surfaces free from deposition. The currents are certainly much weaker than those which are observed in land streams where deposition is gradually building up the stream bed.[5] Also there seems to be no relationship between observed current velocity and type of bottom. The strongest current was found on the slope off the Palos

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[5] These streams, however, presumably have a much heavier load of sediment than ordinarily exists near the sea floor.

rdes Hills where the bottom is covered with mud and a thin mud cover
s noted in Monterey Canyon where the second largest current was
orded. Cores show that mud has been deposited to a considerable
ickness in various other localities where currents were relatively high.
e currents were fully as strong in the canyons which head well out
m the shore and receive sediments as in those which head near the
ast and are kept clean (Shepard and Emery, 1941, p. 90). Two water
mples, procured from about 3 feet above the bottom during times of
aximum observed currents, failed to show any traces of suspended sedi-
ent. In both these cases the bottom was covered with sediment con-
ting of silt and fine sand.

MUDFLOWS AND SUBMARINE LANDSLIDES

A marine process which has been given increasing importance by recent
vestigators is that of mass gravity movement. The cable companies
ve long recognized these submarine slides in connection with the break-
g of their lines on the sea floor; Milne (1897) first called them to the
tention of scientists. The cable breaks have occurred both in asso-
ation with earthquakes and in the absence of seismic activity. It
ems likely that even those accompanying earthquakes are predomi-
ntly the result of sliding of bottom sediments. This contention is sug-
sted by the following:

(1) On land, fault movements such as would break cables, rarely occur
the surface, but landsliding occurs on a large scale during the major
rthquakes.

(2) At the time of the 1929 earthquake near the Grand Banks the
ble breaks covered a territory extending for 700 miles from the epicenter
hepard, 1931, Fig. 1). This would appear to be too great an area
be affected by surface faulting movements.

(3) At the time of the Grand Banks earthquake the cable companies
ported that the cables were buried over extensive areas to such depths
at they could not be recovered with deep drags (De Smitt, 1932).

Furthermore, slumping of sediments, probably in the form of mud
ws, actually takes place in the canyons off the California coast (Shepard
d Emery, 1941, p. 94-108, 116-118). The careful check of profiles along
e heads of the canyons showed that sediments are removed from time
time and that some of these movements take place without any indi-
tion of unusual surface currents or violent wave disturbance. It seems
latively certain that slumping of the bottom has been the cause of
e slides. Finally, the slopes are sufficient in many of the non-
positional environments so that sliding of saturated sediments would
expected.

CONCLUSIONS

The investigation of the sea floor off the California coast has revealed extensive surfaces where deposition of sediment is either completely prevented or is proceeding very slowly with the by-passing of the greater part of the sediment. In this category are large parts of the continental shelves, the upper portions of steep submarine slopes, the walls of submarine canyons, the floors of canyons heading near the coast, and the top and sides of most of the submarine banks and seamounts. Even portions of the inner basins and troughs along the southern California coast may be by-passed by the greater part of the available sediment.

The cause of this nondeposition is not entirely understood; but it is probably the result of internal waves and eddy currents, and to a less extent tidal currents combined with landslides and mudflows. The amount of stirring action of waves at the edge of the shelves is unknown but may be of considerable importance. Tsunamis may also have contributed in the past to the formation of these bare surfaces, particularly on the deep outer banks.

The results of these studies are not easily applied to problems of ancient sedimentary basins, but possible applications can be indicated. An unconformity in a series of marine sediments is commonly interpreted as resulting from the elevation of the area above sea level. Off California however, the elevation of only a portion of a basin would prevent or greatly impede deposition whether or not the surface came above sea level. Also it appears that various environments off the California coast are being by-passed by sediments. Many similar environments may have existed in the ancient seas, so that it would seem advisable to make rather exhaustive studies of unconformable surfaces before concluding that they represent an emergence above sea level. Even the finding of weathered surfaces cannot safely be used as a criterion since some rock decay takes place on the sea floor and results akin to weathering are found where marine organisms have bored into the rock surfaces.

Probably these studies can be more satisfactorily applied to sedimentary basins where deep geosynclines or fault basins are involved than in areas like the Mississippi Valley region where the seas were probably quite flat-bottomed and free from the relief of the present California sea floor. However, even in the mid-continent the possibility of nondeposition arises in connection with such features as the "buried hills" around which some Paleozoic sediments accumulated. Certainly investigators would do well to keep in mind the situation now existing in the seas around the continental margins.

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THE PACIFIC OCEAN[1]

By Dr. H. U. SVERDRUP

SCRIPPS INSTITUTION OF OCEANOGRAPHY, LA JOLLA

Pacific Ocean can be discussed from a number
ent points of view. One could deal with the
of its discovery and exploration from the time
ellan's long and perilous journey up to the
day when clippers of the air cross and recross
n in a few days, or one could discuss its im-
e as a highway of the sea carrying trade be-
rge surrounding countries, or one might con-
as determining the routes for the migration
and the spreading of culture from island
o island group and from continent to conti-
shall not attempt to discuss the Pacific Ocean
y of these points of view, but shall, instead,
h the water masses themselves and with the
of prevailing currents, and shall indicate how
n influences the climate and the weather of the
ding land and how the productivity of the sea,
becoming increasingly important to the econ-
nan, varies from one region to another because
haracter of the currents.

starting point let us examine the distribution
ce temperature over the Pacific Ocean in the
f August. The striking features are, in the
ce, the vast extent of the tropical areas in
he surface temperature is very high, above
75° F.), and, in the second place, the tongues
emperature which extend towards the Equator
ne western boundaries of the ocean, that is,
ne coasts of North and South America. Due
intrusion towards the Equator of these cold
he width of the tropical region is much smaller
American side than on the Asiatic-Australian
his contrast between west and east is closely
to the character of the currents, and we shall
return to this relationship. The point which
emphasized now is that the surface waters of
ific Ocean are very warm over large areas in
ics, moderately warm over smaller areas in
latitudes, and cold only in high northerly and
itherly regions.

vations of the temperature at subsurface levels
owever, that only a relatively thin surface
heated and that the enormous water masses
ll all the deep basins of the Pacific Ocean are
ving a temperature which lies less than 2° C.
reezing. Thus, to the south of the Aleutian
the very surface waters in summer are mod-
warm, but below a depth of 60 meters the temperature varies between 3° and 1.6° only. In the trade-wind region in the North Pacific high surface temperatures are encountered, but below a thin top layer the temperature decreases rapidly with depth and below 1,500 meters again remains below 3°. In the region of the trade-winds of the Southern Hemisphere a similar temperature distribution is found. In 50° S near the center line of the South Pacific, the temperature is above 5° down to a depth of 900 meters, but below 1,500 meters is nearly the same as that observed in the other localities.

Below a depth of 2,000 meters the salinity of the Pacific waters is nearly constant, the salt content varying only between 34.6 and 34.7 parts per thousand (per mille), that is, only by about 0.1 gram in one kilogram of water.

The deep water of the Pacific is of greater density than the waters near the surface, and in the Pacific as well as in all other oceans we find the water masses arranged in stable stratification, that is, we always find the denser waters near the bottom and the lighter water masses at the surface. Now, the density of the ocean waters is changed only when the water is in contact with the atmosphere where it may be heated or cooled or where the salinity may be increased or decreased by evaporation or precipitation. In general, we therefore find certain regions where the surface waters attain a great density, and from where they sink to the level at which the density attained at the surface prevails. These are regions in which the subsurface water masses are formed. The formation of the uniform deep water of the Pacific was, however, for a long time puzzling to oceanographers because no region in the Pacific Ocean could be found in which such water was formed at the surface and sank towards the bottom. Over wide areas in the northwestern North Pacific the temperature is in winter as low or lower than the temperature of the deep water but the salinity remains so low that the water is much lighter than the deep water and can not sink towards the bottom. Similarly, in the Antarctic part of the South Pacific no sinking of cooled surface water takes place. The puzzle was solved when it was realized that the deep water of the Pacific is not formed in that ocean but originates mainly from the Atlantic Ocean, where sinking of surface water takes place both in high northerly and high southerly latitudes.

In the Atlantic Ocean deep water of high salinity ($34.9^0/_{00}$) and relatively high temperature (2.5° C.) is formed to the north where the high salinity water

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, New Series, No. 147.

of the Gulf Stream is cooled in winter and attains such a high density that it sinks to great depths. The salinity of the North Atlantic deep water over large areas is increased by addition of high salinity water flowing out from the Mediterranean. In the Antarctic region to the south of the Atlantic the density of the water is increased by cooling and freezing of ice, leading to the formation of a bottom water of low temperature (– 0.6° C.) and moderate salinity ($34.6^{0}/_{00}$). These two types of deep water spread south and north, respectively, and the spreading can be recognized in vertical sections showing tongue-like isotherms and isohalsines. Mixing takes place and, due to this, a fairly uniform body of water is formed to the north of the Antarctic Continent within the region of the circumpolar Antarctic Current which circles the Antarctic Continent as the greatest current of all oceans. Within the greater part of this body the temperature varies only between 2.5° and 0°, and the salinity between $34.65^{0}/_{00}$ and $34.75^{0}/_{00}$. In the Atlantic and Indian sectors the influence of the warm and saline deep water of the northern seas and the cold and less saline bottom water of the Antarctic is evident, but otherwise the striking feature is presented by the very small differences in temperature and salinity within the entire region. The water is particularly uniform in the Pacific sector and it is this uniform circumpolar water which spreads north and fills the entire basins of the Pacific, being slightly diluted by low salinity water from higher levels. In the South Pacific a vertical circulation provides for exchange of water with the Antarctic circumpolar water mass, but in the North Pacific such circulation is lacking. There the small inflow of deep water from the south appears to be compensated by an outflow to the Indian Ocean between the islands of the East Indian Archipelago.

A vertical section showing the distribution of temperature and salinity in the Pacific Ocean clearly demonstrates the point that on the whole the waters of the Pacific are very cold and that only a relatively thin surface layer is heated. Between the deep water and the warm surface layers intermediate water masses of low salinity are present. These are formed partly in the Antarctic and partly in the Arctic regions of the Pacific Ocean and have their counterparts in the Atlantic.

Let us now return to conditions near the surface of the ocean in order to examine how the general distribution of temperature in the surface layers is related to the prevailing currents. Keeping in mind the picture of the distribution of surface temperature it is readily recognized that the regions of low temperature off the coasts of North America and South America are regions in which the general currents flow from higher to lower latitudes bringing water of low temperature closer to the Equator. In contrast the
regions in the western part of the Pacific where e
sive warm water masses are found are regions
the general direction of the current is from lo
higher latitudes such that warm water is carried
from the Equator.

The direction of the surface currents corres
more or less to the direction of the prevailing
over the different parts of the ocean, with such e
tions as must be expected because of the coast
Thus, the relatively narrow and swift Kuroshio
coast of Japan is not directly related to the local
but runs in winter partly against the wind, bu
current must be considered as the necessary co
ation of the North Equatorial Current which
from east to west under the influence of the prev
trade winds.

Among the surface currents of the Pacific
there is, however, one which is not obviously r
to the prevailing winds nor to the character o
coast lines, and that is the Equatorial Counter
rent which is embedded as a narrow and swift c
towards the east between the west-flowing Nort
South Equatorial Currents. The nature of the
torial Counter Current has only recently b
clearly understood. It is explained as follo
Montgomery and Palmén: The prevailing trade
exert a stress on the sea surface which, besides
tributing towards maintaining the equatorial cu
also lead to a piling-up of light surface water a
the western boundaries of the ocean. From o
graphic observations it is evident that such a pili
takes place because off the American coast the
ness of the warm surface layer is as little as 20 m
whereas off the Philippines and New Guinea th
responding thickness is 200 meters or more.
consequence of this piling-up the sea surface ac
rises from east to west, the rise amounting to
65 centimeters. This sloping surface has not
determined, of course, by precision leveling, but
clusions as to its existence are based on convi
oceanographic evidence. The slope in the trade-
regions is balanced by the stress which the
exerts on the sea surface, but between the trade
regions lies the equatorial belt of calms where no
stress acts on the sea surface. Therefore withi
calm belt the water must flow downhill from the
ern to the eastern side of the ocean and the co
current represents this downhill flow. Fric
forces prevent the water from attaining as high
cities as would correspond to a free fall of 65
meters. If there were no friction a counter cu
should reach a velocity of nearly seven knots, th
seven nautical miles per hour, when approachin
American coast, but the maximum velocity lie
tween 1 and 2 knots only.

Owing to the friction, a transverse circulation

within the counter current, which is quite
nd confined to movement of the warm surface
Theoretical examinations by Defant lead to
t that this transverse circulation should have
racter that water is drawn towards the sur-
he northern boundary of the current and at
tor, and sinks at the southern boundary of
ter current. Such a transverse circulation
exists in the Pacific, where detailed measure-
temperature, salinity and chemical constitu-
made by the *Carnegie* in 1929. This circula-
has an effect on the distribution of organisms
wherever subsurface water is drawn towards
ace, conditions for development of organ-
favorable. The subsurface waters are rich
nutrients such as phosphates and nitrates
en brought near the surface where there is
h that photosynthetic activity can go on, a
p of plants will develop followed by large
ons of animals. During the crossing of the
by the *Carnegie* in 1929 net hauls were made
aination of the microscopic organisms, and
g to these the variation in total plankton
erfectly with the above reasoning. Maximum
of plankton were found at the northern boun-
the counter current and near the Equator,
bsurface water was drawn towards the sur-

ounter current does not appear in the distri-
f surface temperatures because it is a feature
urface layers only, it is a shallow current
found completely within one uniform clima-
area, the Tropics. The other major currents
ent in the distribution of the temperature, as
ady been pointed out, but from a chart of
ace temperature and also from a chart show-
haracter of the surface currents it appears as
ansitions in the ocean are gradual, as if the
n the character of the water when passing
ver to higher latitudes or from west to east
ace in such a gradual manner that no boun-
ions between different currents can be recog-
Examination of subsurface conditions reveals,
, that this impression is quite erroneous and
the contrary, well-defined water masses are
separated by relatively narrow regions of
n.

ler to recognize these water masses it is neces-
plot the data from the sea, particularly the
ture and the salinity, in a special manner.
cedure is best illustrated by means of a dia-
Fig. 1). In this diagram are shown the ver-
tribution of temperature and salinity at two
in the Gulf Stream off North Carolina. Ex-
these curves only there appears to be little similarity between the conditions at the two stations. Thus, at the one which was closest to the coast a temperature of 15° was encountered at a depth of 300 meters, whereas at the station at greater distance from the coast the same temperature was encountered at the depth of 650 meters. The discrepancy between conditions at the two stations disappears, however, if the observed temperatures are plotted against the observed salinity, as has been done in the diagram to the right. From this diagram it is seen that the water which at the one station was found to be between the depths of 277 meters and 461 meters is of exactly the same character as that found at the other station between 490 and 790 meters. Or, in other words, a definite relation exists between the temperature and the salinity such that within the same water mass the corresponding values of temperature and salinity fall on a well-defined curve. Therefore, by plotting the observed temperatures and salinity in a diagram one can recognize a given water mass of different character.

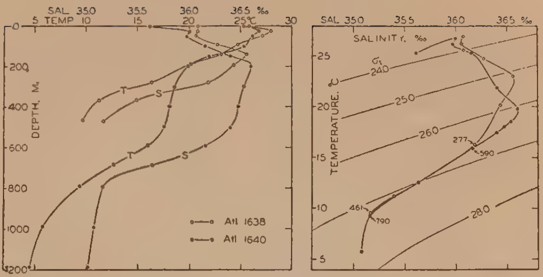


FIG. 1. *Left.* Temperature (T) and salinity (S) at two stations off Onslow Bay, N. C., plotted against depth. *Right.* Temperature and salinity at the same stations plotted against each other.

Applying this examination to the South Pacific, one finds there several well-defined regions within which typically different water masses are present (Fig. 2), the Subantarctic which occupies the southern part of

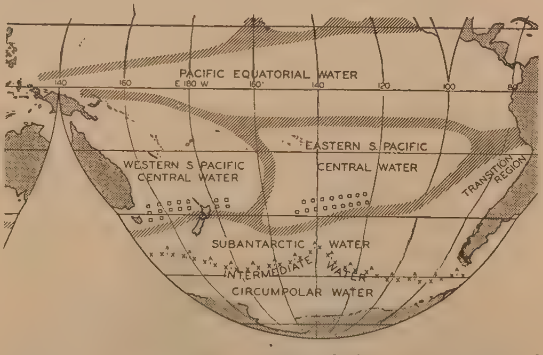


FIG. 2. Regional distribution of the water masses of the South Pacific. Areas in which the central water masses are formed are indicated by squares, area in which intermediate water is formed is shown by crosses.

the ocean and extends along the coast of South America to about 15°S, the eastern and western Central Water Masses and the Equatorial Water Mass, which is wide in the east and narrow in the west. The character of these water masses is shown in Fig. 3.

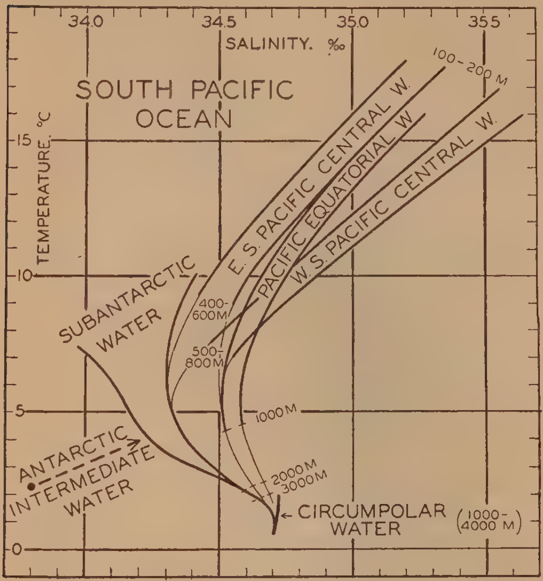


FIG. 3. The water masses of the South Pacific shown in a temperature-salinity diagram.

In this diagram no single T-S curves are entered but, instead, bands are shown, the significance of which is that corresponding values of temperature and salinity fall inside of the lines which represent the boundaries of the bands.

In the diagram the uniform circumpolar water appears as a short piece of a curve because the salinity of that water is nearly constant at 34.7$^0/_{00}$ and the temperature varies only between 2° and 0.5°. The deep water below the other water masses is nearly similar to the circumpolar water, as is evident from the fact that all curves converge at their lower ends. Above the deep water the Antarctic Intermediate Water shows up by its low salinity values and above this again are found the other water masses. The Central Water Mass of the Western South Pacific is similar to the corresponding water masses of the Indian and Atlantic Oceans, being formed in a similar manner under similar external conditions. The Eastern Water Mass has a somewhat lower salinity, probably because of admixture of Subantarctic water, and the Equatorial Water Mass is intermediate between the two and must, therefore, mainly originate in the South Pacific.

Turning to the North Pacific, we encounter a similar distribution of water masses. Again two Central Water Masses are present (Fig. 4), one small e and one large western, and to the north of th found a large body of Subarctic water. It m

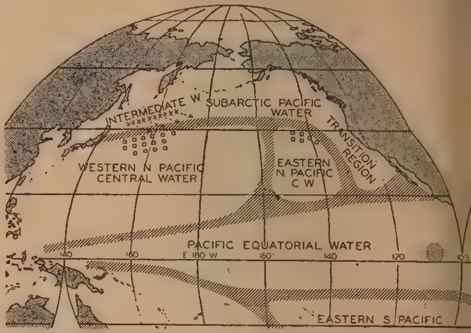


FIG. 4. Regional distribution of the water mas the North Pacific. Areas in which the central masses are formed are indicated by squares, area in intermediate water is formed is shown by crosses.

mentioned here that in the North and South A and Indian Oceans only one Central Water M present, but in the North and the South Pacific C two are found, probably because these oceans ar wide and because frequently two areas of atmos high pressure are present over these seas.

The character of the water masses can be illus by a diagram similar to that used for showin water masses of the South Pacific (Fig. 5). the uniform nature of the deep water is evident the convergences of the different curves. Abo deep water intermediate water is present, but th

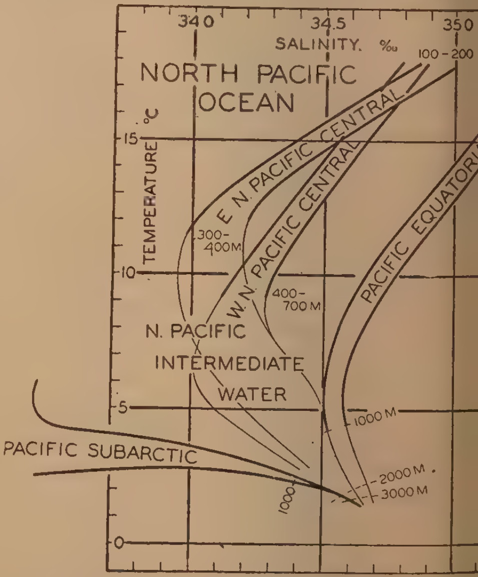
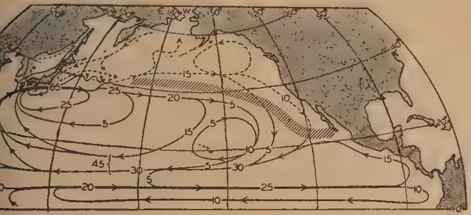


FIG. 5. The water masses of the North Pacific in a temperature-salinity diagram.

of this intermediate water is more complicated some regions two salinity minima appear. The Water Masses are of much lower salinity e corresponding ones in the South Pacific, indi- hat the Equatorial Water Mass must originate South Pacific as was already pointed out. The ic Water has a low temperature and a low which increases with depth until the values leep water are reached. The one feature to be is that, except for the Eastern North Pacific Water Mass, these different water masses are defined and all are separated by relatively regions of transition.

circulation of the North Pacific can now be ed in a more definite manner than by maps the surface currents, because a chart can be d showing the general direction in which water ported by the ocean currents and the amounts r carried by the different branches. Such a shown in Fig. 6 in which the transport by the



. Transport by the currents of the North Pacific. ndicate direction of transport and numbers give of waters expressed as millions of cubic meters nd.

t branches of the current system is given in of cubic meters per second. Thus the maxi- ansport by the Japan Current is as high as 65 cubic meters per second, whereas the Califor- rent carries about 10 million cubic meters per As a comparison it may be mentioned that ssissippi River carries on an average 120,000

chart shows the equatorial currents between he counter current is embedded. It shows the Kuroshio, which is part of a big gyral in the Pacific; it shows the presence of a smaller between the Hawaiian Islands and North a, and it also shows how water of the Kuroshio s mixed with the cold water of the south-flowing such that in the Northwestern Pacific a new nass, the Subarctic Water Mass, is formed by re cooling and by dilution owing to excessive tation. This water flows to the east as a cold , the Subarctic Current of the Pacific, part of bends south and follows the west coast of the United States and Lower California, until it meets and becomes mixed with the Equatorial waters.

It is not possible to prepare a similar map for the South Pacific because sufficient data are not available, but from the information at hand it is certain that, in general, the currents of the two parts of the ocean are mirror images of each other. The California Current is a counterpart of the Peru Current, which is even more conspicuous and exerts a greater influence upon the distribution of organisms in the sea and upon the climatic conditions.

I have attempted to give a brief review of the structure of the water masses of the Pacific and the relation of prevailing currents to this structure. In conclusion a few words may be added as to the meteorological significance of our increased understanding of ocean circulation and as to the relation of the productivity of the sea to the water masses and currents. It has long been recognized that the oceans exercise a thermostatic control on the climate. The sea receives in summer a great surplus of radiation from the sun and the sky which in that season is mainly used for raising the temperature of the water, and in winter is given off to the air when cold winds blow from the continent, or is used for evaporation. Only recently has it been possible to examine more closely in what regions the heat is given off to the atmosphere and where the maximum evaporation takes place. According to a study which is now in progress, the warm waters of the Kuroshio give off in winter enormous amounts of heat as they flow north, whereas only small amounts are released over the eastern part of the ocean.

Off Japan the maximum amounts of heat given off are greater than 240 gm cal/cm^2/day, that is, about half the amount which in that region is received in summer. Similarly, the evaporation from the waters of the Kuroshio reaches in winter values greater than 0.8 cm/day, corresponding to a transfer of about 480 gm cal/cm^2/day of latent heat, or about as much as is received in summer. Evidently, the exchange of heat and the evaporation from the sea surface is closely related to the oceanic circulation and is very localized. Therefore, in winter the energy for the atmospheric disturbances in middle latitudes is supplied *by the sea in restricted areas.* These very areas have long been known to be those in which the atmospheric disturbances, the traveling cyclones, are formed, and the present results serve therefore to illustrate the close interaction between the atmosphere and the oceans.

As far as the productivity of the sea is concerned it should be borne in mind that the sea can support large populations of plants and, consequently, provide food to large numbers of animals only in regions where phosphates, nitrates and other plant nutrients are available in the surface layer where so much light penetrates that photosynthesis is possible. Phosphates and nitrates are present in relatively high concentrations in the subsurface layers where organic remains are decomposed, but in the surface layers the available amounts are depleted, owing to the activity of the plants, particularly the microscopic floating plants which represent the main animal food. In order to provide for continued production of plants, water from subsurface depths must be brought to the surface and this takes place in regions of intense mixing, in regions where in winter excessive cooling of the surface layer occurs such that convection currents reaching to considerable depths develop, and in regions where upwelling of subsurface water takes place. Upwelling of subsurface water is particularly conspicuous along the west coast of the United States and off the west coasts of Chile and Peru, and the waters off these coasts are known for their large fisheries. It may be enough to mention that during the last few years an average of about 500,000 tons of sardines have been caught off the American west coast and that according to estimates the amount of fish caught by the guano birds off Peru probably passes 3,000,000 tons a year. Regions of winter cooling and consequently thorough mixing to considerable depths are found in the Gulf of Alaska, around the Aleutian Islands, and in Bering Sea, where again fisheries of the greatest importance take place, and regions of intense mixing and partly of winter cooling are around Japan, where probably the most intensiv ing in the Pacific is undertaken. The large open areas are not devoid of life, but the populations reach such density that fishing operations ca undertaken with success. In the regions which been mentioned and in regions adjacent to is where considerable stirring occurs detailed and sive work has to be carried out in order to learn about the factors which control the productivity sea and which place a limit on the extent to the sea can be exploited. At the Scripps Insti of Oceanography we shall for some time to con tinue an intensive study of the productivity waters off southern California as one of our objects.

Many of the conclusions which have been pres here are based on meager data, and many featu the picture which has been developed may have modified. Only the average state of the ocea been dealt with because oceanography has no vanced far beyond the descriptive stage and be the understanding of the processes which mainta average conditions is still incomplete. The field us is enormous and it is my hope that in the f increasing efforts will be directed towards fr exploration of the largest but least known oceans, the Pacific Ocean.

Contribution No. 148

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GRAVITY CORING INSTRUMENT AND MECHANICS OF SEDIMENT CORING

BY K. O. EMERY AND R. S. DIETZ

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ABSTRACT

A gravity-type coring apparatus, which is used on the research vessel *E. W. Scripp* of the Scripps Institution of Oceanography for taking sediment samples of the ocea floor, is described. With this instrument more than 200 cores have been taken in man types of sediment. The 174 mud cores have an average length of 6 feet, 3 inches an a maximum length of 16 feet, 9 inches.

Data from a number of experiments and from field coring operations were analyse in order to improve the design of the device and to permit proper interpretation o core samples. A detailed study was made to explain the observation that the length o the cores averaged about 50 per cent of the depth of penetration of the core barrel Laboratory coring experiments using mud of uniform water content show that, a the core barrel penetrates the mud, progressively smaller increments of core ar added throughout the entire depth of penetration. However, studies of cores take on a tidal flat and others obtained in field operations show that the size of cor increments per unit of penetration remains practically constant with increasin penetration.

INTRODUCTION

During the year 1938, a number of problems connected with the geology of the Pacific Ocean floor off California were investigated by a group o geologists under the direction of Dr. F. P. Shepard. Early in the work need developed for an inexpensive method of taking long cores in ocean floor sediments. In early investigations of ocean floor sediments, core were obtained by using simple weighted tubes. Later instruments obtained their energy from exploding cannon powder (Piggot, 1936) o from the hydrostatic head of sea-water at the site of coring (Varney and Redwine, 1937). Modification of the simple and inexpensive gravity type resulted in the development of a large corer costing only about $100. Since 1938, a total of 229 cores having a maximum length o nearly 17 feet have been taken with this instrument from the research vessel *E. W. Scripps* off the coast of California and Mexico and in the Gulf of California.

It was noted that the core-length was commonly only 40 to 70 per cent of the distance of penetration of the core-tube. The method by which this shortening takes place should be known for proper interpretation

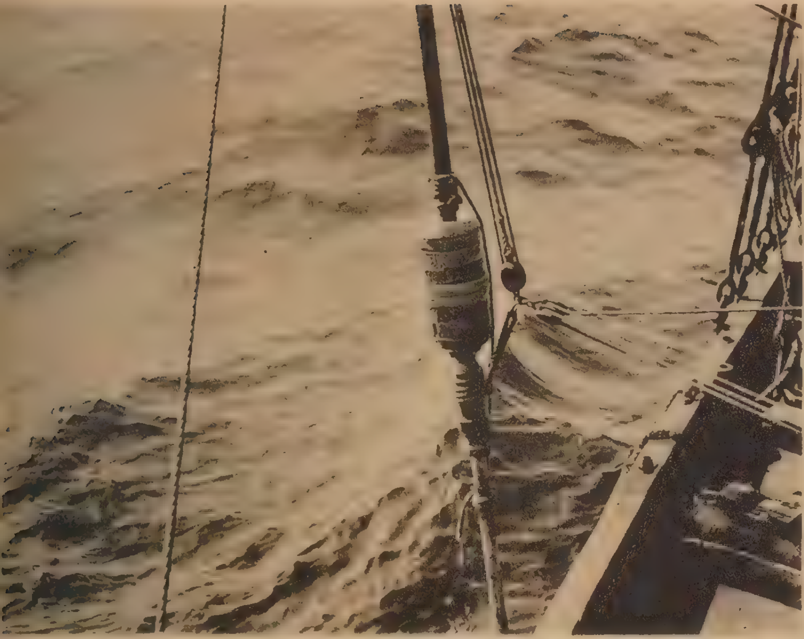

FIGURE 1. CORER OVERSIDE
Note method of handling with blocks and tackles. Photograph by Cliff Johnson

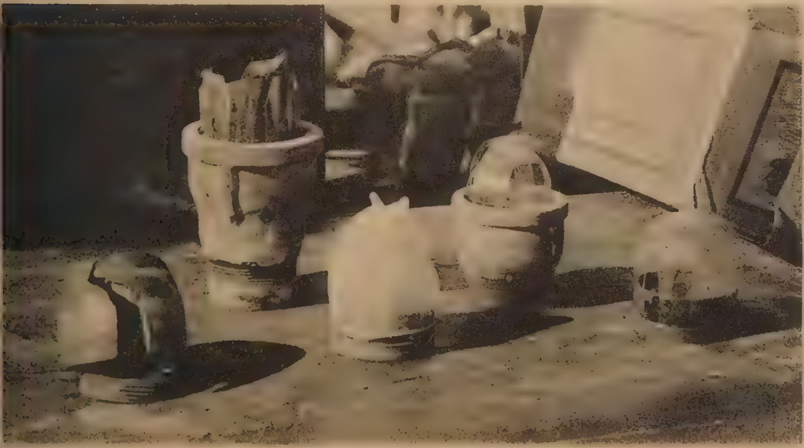

FIGURE 2 NOSES AND CORE-RETAINERS
From right to left: Core-retainer made by cementing strips of celluloid (with acetone) to another strip attached to a thin steel sleeve; core-nose and celluloid retainer for a 2.06-inch I.D. tube; thin rubber sleeve mounted on celluloid strips forming a complete core-retainer; core nose and retainer for 2.44-inch I.D. tube—containing a portion of a core; core-nose after encountering rock.

CORING DEVICE

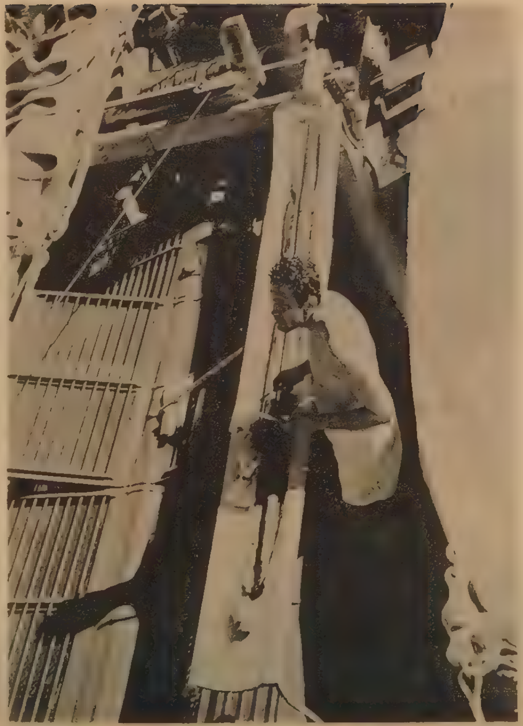

Figure 1. Core on Sectioning Trough
The 15-foot core has been cut into two portions and while still in the opened celluloid core-liner is being sectioned and sealed in bottles.

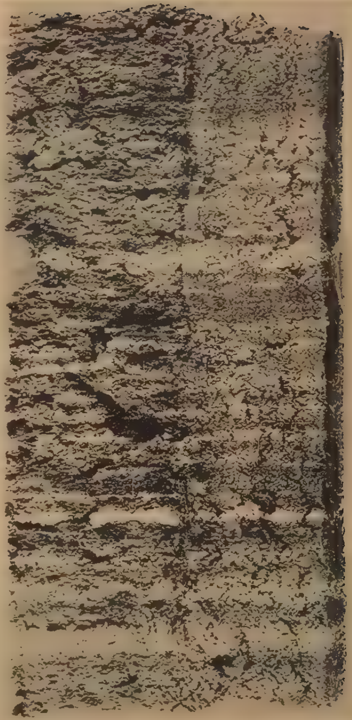

Figure 2. Laminae in a Partially Dried Core of Diatom Mud from Gulf of California
Note characteristic absence of disturbance.

CORE SAMPLES

of the cores. Accordingly, a number of experiments were undertaken to determine the factors which cause shortening and the manner in which it takes place.

ACKNOWLEDGMENTS

This investigation was made possible through the co-operation of the Geological Society of America, the Scripps Institution of Oceanography, and the University of Illinois. The use of the vessel *E. W. Scripps* permitted the collection of cores on a number of cruises off California during 1938 and on expeditions to the Gulf of California during 1939 and 1940.

The writers wish to express their especial appreciation to Dr. F. P. Shepard, at whose suggestion the corer was devised, and to Dr. Roger Revelle, who made available results of the laboratory study of the cores. Both Doctor Shepard and Doctor Revelle contributed ideas toward the construction and operation of the corer and also aided in the study of the results of experiments. Dr. M. Juul Hvorslev kindly read the manuscript and offered suggestions. Appreciation is also expressed to Mr. Carl Johnson of Scripps Institution who constructed the instrument, and to Capt. E. H. Hammond of the vessel *E. W. Scripps,* who devised a method of handling it on shipboard.

CORING DEVICE

CONSTRUCTION

Because core-tubes and noses, even though constructed of expensive alloy steel, usually are badly bent on striking rocky or sandy bottom, an effort was made to use common pipe and plumbing connections throughout. Rugged and simple construction reduced interruption of operations to a minimum.

The corer consists essentially of a shaft, weight, and core-tube (Fig. 1; Pl. 1, fig. 1). The shaft is a 2.44 inch I. D. standard pipe 8 feet long. Several small holes permit water to escape as the device is lifted from the sea. On the shaft is a series of nine 60-pound lead weights, roughly streamlined. The complete corer, weighing about 650 pounds in air, was operated with ⅜-inch wire cable on the large winch of the *E. W. Scripps.* Under some conditions, cores were taken with only enough lead attached to the instrument to give it a total weight of about 300 pounds. This lightened corer permitted the use of a smaller crew and only 3/16-inch wire cable.

Screwed onto the lower end of the shaft and forming a shoulder to take the thrust of the lead weights is a valve housing (Fig. 1) which consists of a short pipe 4 inches in diameter with a reducer at each end. Inside is a large rubber stopper, resting loosely in a brass seating. This valve

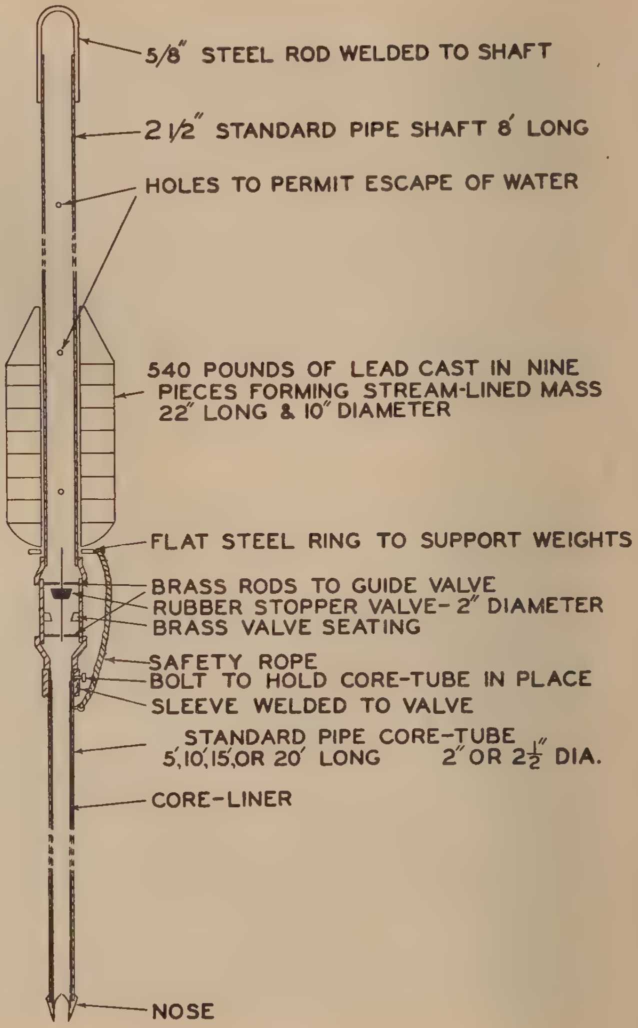
5/8" STEEL ROD WELDED TO SHAFT
2 1/2" STANDARD PIPE SHAFT 8' LONG
HOLES TO PERMIT ESCAPE OF WATER
540 POUNDS OF LEAD CAST IN NINE PIECES FORMING STREAM-LINED MASS 22" LONG & 10" DIAMETER
FLAT STEEL RING TO SUPPORT WEIGHTS
BRASS RODS TO GUIDE VALVE
RUBBER STOPPER VALVE- 2" DIAMETER
BRASS VALVE SEATING
SAFETY ROPE
BOLT TO HOLD CORE-TUBE IN PLACE
SLEEVE WELDED TO VALVE
STANDARD PIPE CORE-TUBE 5',10',15',OR 20' LONG 2" OR 2½" DIA.
CORE-LINER
NOSE

FIGURE 1.—*Coring device*

prevents occasional loss of core by suction during withdrawal from the bottom, prevents washing out of the relatively fluid upper part of the core while the device is being hoisted through the water, and prevents the weight of the water column in the shaft from forcing out short cores after the instrument is lifted from the sea. Experiments showed that at the velocities used the valve does not inhibit the upward flow of water enough to influence appreciably the length of cores.

Below the valve is the core-tube, a 2.06 in. I.D. (2.38 in. O.D.) or a 2.44 in. I.D. (2.87 in. O.D.) standard pipe. Attachment is made by thrusting the tube into a sleeve and against a shoulder of the valve housing where it is clamped with a set screw. The lengths of core-tubes range up to 20 feet depending on the type of sediment expected. In recent work a removable core-liner has been placed inside the core-tube. This liner consists of a strip of 15-gauge celluloid reinforced at each end and rolled into a cylinder before being inserted into the tube. Its presence reduces the inside diameter of the core-tube approximately 0.04 inch.

Screwed to the lower end of the core-tube is a core-nose (Pl. 1, fig. 2) having an inside diameter ½ to ¼ inch less than that of the core-liner. Forming part of the nose is a core-retainer which consists of strips of celluloid thrust into a thin rubber sleeve. The strips of celluloid extend upward and inward from the core-nose (Pl. 1, fig. 2) in such a manner that during the entrance of a core they are pushed back against the tube wall. If the core starts to slip out, however, the strips close the opening, thus preventing further loss. The thin rubber sleeve makes the core retainer almost water tight—a requirement for the retaining of sand cores. This celluloid and rubber core-retainer proved far superior to numerous other types which were devised and tested.

OPERATION

After the instrument is assembled and lowered into the water (Pl. 1, fig. 1), it is dropped slowly until within about 300 feet of the bottom as indicated by the ship's echo sounding device and is then allowed to run rapidly with only a slight brake pressure to insure a vertical descent.[1] Velocities of 12 to 21 feet per second are attained just before striking bottom, regardless of the length of cable paid out. In depths shallower than 3000 feet a slackening of cable indicates that the instrument has hit bottom. Between depths of 3000 and 6000 feet, a pointer attached to an accumulator spring has been found useful, but at greater depths and in rough weather there is some difficulty in determining the instant

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[1] An attempt to use wings or longitudinal vanes to aid the corer in maintaining a vertical position resulted in excessive fouling of the cable and proved unnecessary.

TABLE 1.—*Summary of Coring Results*

Type of sediment	Corer		No. of trials	Average core-length (inches)	Maximum-minimum core-length (inches)	Average penetration (inches)	Maximum-minimum penetration (inches)	Core-length to penetration ratio
	Approximate weight (pounds)	Diameter of tube (inches I. D.)						
Red clay	300	2.06	2	97 (1)*		135 (2)	132–138	73 (1)
Diatom mud	600 Emery-Dietz	2.44	23	156 (22)	48–201	>255 (23)	>152–>288	<63 (23)
	600 "	2.06	3	135 (2)	81–190	>134 (2)	>132–>136	<59 (2)
	250 "	2.44	9	87 (8)	48–147	121 (8)	72– 204	68 (7)
	250 "	2.06	13	66 (13)	38–116	126 (4)	96– 144	53 (4)
Green clayey or silty mud	600 "	2.44	7	104 (6)	49–180	>189 (7)	>106–>264	<53 (6)
	600 "	2.06	32	78 (30)	28–120	158 (29)	72–270	51 (23)
	250 "	2.44	10	66 (8)	49–85	106 (7)	81–132	60 (7)
	250 "	2.06	39	54 (37)	11–90	94 (20)	60–144	63 (15)
	150 (Ekman)	2.06 and 1.50	24	21 (24)	12–69	54 (17)	15–78	48 (17)
Sandy or shelly mud	600 Emery-Dietz	2.44	3	64 (3)	32–85	>158 (3)	>131–>180	<41 (3)
	600 "	2.06	40	52 (33)	20–91	>139 (36)	48–>186	41 (24)
	250 "	2.44	5	37 (5)	14–75	81 (4)	41–120	54 (4)
	250 "	2.06	11	32 (7)	15–64	38 (6)	24–48	51 (2)
	150 (Ekman)	2.08 and 1.50	5	12 (5)	7–20			
Sand, shells, or pebbles	600 Emery-Dietz	2.44	9	21 (7)	2–42	55 (7)	6–84	45 (6)
	600 "	2.06	38	21 (18)	4–65	57 (14)	18–115	41 (9)
	250 "	2.44	1	6 (1)		10 (1)		60 (1)
	250 "	2.06	33	16 (7)	6–23	37 (20)	11–65	72 (4)
	150 (Ekman)	2.06 and 1.50	12	5 (7)	3–15	8 (1)		
Gray clay Pre-Recent?	600 Emery-Dietz	2.44	9	15 (8)	4–42	30 (8)	6–75	43 (7)
	600 "	2.06	1	4 (1)				
	250 "	2.44	2	0		18 (2)	15–21	
Rock	600 "		16	— (6)				
	250 "		12	— (6)				
	150 (Ekman)		9	— (2)				

* The number of trials on which each average is based is indicated by the figure within parentheses.

f impact.[2] When bottom is reached, the winch is stopped immediately o prevent kinking of cable.

The undisturbed core is extracted from the core-tube by withdrawing nd opening the celluloid core-liner (Pl. 2, fig. 1). Five-inch lengths of ore are cut, scraped, described, and placed in mason jars or are sealed n cans.

RESULTS

Examination of Table 1 shows that for each type of sediment the longst cores were taken by the instrument having the greatest weight and he largest diameter core-tube. The average length of 22 cores of diatoaceous mud taken with the large corer is 13 feet. One of these cores is 6 feet 9 inches, and seven others are more than 15 feet long.

It will be noted that nearly 75 per cent of the misses resulted from the triking of sand or rock. In later work much better results for sandy ediments were obtained through the use of core-retainers. Data on a umber of cores taken by a modified Ekman device (Trask, 1932, p. 11-3) are included in Table 1 for comparison.

The speed of operation is shown by the fact that as many as 11 trials ave been made in a single day in water ranging from 50 to 400 feet in epth. Also, off Newport, California, four cores were taken from an averge depth of 800 feet in about one hour. Operations in deeper water are omewhat slower, but the device has been used successfully at depths s great as 12,200 feet.

FACTORS CONTROLLING LENGTH OF CORES AND DEPTH OF PENETRATION

GENERAL CONSIDERATIONS

A number of factors control the length of cores, such as shape of the ose, diameter, wall-thickness, length of the core-tube, inner and outer all-friction, weight of the corer, velocity of coring, and the character of ediment. Data on about 270 cores, taken in actual operations with varius combinations of nose, tube, and weights, permit the evaluation of ertain of these factors. A great deal of additional information came rom numerous experiments in which coring velocity and type of sediment ould be more easily controlled than in field operations.

CORE-NOSE

A number of experiments were made for evaluating the effect of the ore-nose on the length of mud cores. Table 2 gives a comparison of core-

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[2] A preliminary attempt was made to develop a mechanical sound emitting apparatus which, when ttached to the coring instrument, would flash a signal to the ship's echo sounding device at the instant hat the corer reached bottom. The attempt did not succeed, but it is probable that such an apparatus an be employed.

Table 2.—*Effect of nose in coring mud and stiff clay*

Stream bed; St. Joseph, Illinois, April 24, 1939

Sediment	Nose	Velocity (ft./sec.)	Weight (lb.)	Penetration (inches)	Core-length (inches)	Core-length/ penetration
Mud	without nose	11.4	31	13.5	11.3	0.84
Mud	with nose	11.4	31	15.3	10.3	.67
Mud	without nose	11.4	89	22.0	15.0	.68
Mud	with nose	11.4	89	25.0	18.5	.74
Mud	without nose	19.7	31	19.0	14.0	.74
Mud	with nose	19.7	31	23.5	15.8	.67
Stiff clay	without nose	40.0	31	15.0	9.5	.63
Stiff clay	with nose	40.0	31	20.5	18.8	.92

Table 3.—*Effect of core-nose in small-scale experiments with clay*

Scripps Institution, August 28, 1938

Tube	Nose I. D. (inches)	Nose O. D. (inches)
F (Flared-end)	0.71	0.83
S (Square-cut end)	.59	.68
T (Tapered end)	.49	.57

All tubes above nose have same diameter as nose of square-cut tube.

Tube	Velocity (ft./sec.)	Weight (lb.)	Penetration (inches)	Core-length (inches)	Core-length/ penetration
S	13.8	1.4	4.8	1.9	0.40
T	13.1	1.5	4.6	3.2	.70
S	7.9	10.9	11.6	3.2	.28
T	7.9	10.9	11.2	3.6	.32
F	7.9	7.8	11.1	2.8	.25
S	7.9	7.8	9.2	3.2	.35
T	7.9	7.8	10.8	3.2	.30
F	6.6	7.8	10.4	2.6	.25
S	6.6	7.8	8.1	2.6	.32
T	6.6	7.8	7.4	2.7	.37
F	4.6	10.9	9.8	2.4	.24
S	4.6	10.9	9.5	3.0	.32
T	4.6	10.9	9.2	3.4	.37

lengths obtained in experiments in mud using a 2.06 inch I.D. core tube alternately with and without a nose (1.87 in. I.D.) attached. It will be noted that the use of the nose (Pl. 1, fig. 2) generally resulted in a longer core and a greater penetration. A longer core also was obtained when a nose was used on tubes hammered into mud (Fig. 8). Smaller scale experiments made with glass tubing also produced similar results (Table 3).

TABLE 4.—*Effect of nose in coring sand*

Scripps pier, August 24, 1939

Velocity (ft./sec.)	Weight (lb.)	Tube Diameter (inches I.D.)	Nose I. D. (inches)	Penetration (inches)	Core-length (inches)	Core-length / penetration
13.8	30	2.06	no nose	7.0	6.7	0.96
19.6	30	2.06	no nose	8.7	8.0	.92
21.9	30	2.06	no nose	9.2	8.7	.95
13.8	30	2.06	1.94	6.8	4.9	.72
19.6	30	2.06	1.94	9.0	7.0	.78
21.9	30	2.06	1.94	9.5	8.5	.89
13.8	30	2.06	1.82	4.7	3.4	.72
19.6	30	2.06	1.82	6.7	4.6	.69
21.9	30	2.06	1.82	8.6	5.4	.63
20.4	25	1.62	no nose	9.1	7.3	.80

Judging from the experimental results, it seems that the core-nose has two main functions: it permits the taking of longer cores and it allows greater penetration[3] in mud (Pratje, 1935, p. 26). The mud column passing through the nose has a diameter slightly less than that of the tube wall. This allows the core to pass upward with less friction against the wall than would be the case were no nose used. Similarly, the larger outer diameter of the nose causes a thrusting aside of the mud so that it does not drag so much on the surface of the pipe. In contrast to this action for mud, other experiments indicate that longer sand cores are obtained if no nose is used (Table 4).

CORE-TUBE

In order to evaluate the effect of the core-tube diameter, a series of cores was taken in the muddy bottom of a recently diverted stream. The results are shown in Table 5. It will be noted that the ratio of core-length to penetration increases and that the penetration decreases progressively with increasing tube diameter even though the larger tube were heavier. As the diameter increases from 0.60 inch to about 2.4 inches, the core-length also increases. In these experiments no gain i core-length was obtained through the use of core-tubes larger than 2.4

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[3] The depth of mud smearing on the outside at the core tube is taken as a measure of the penetration. Due to the slight downward deflection of mud below the core-nose, this is not an exact measure of the thickness of mud penetrated but serves as a close approximation.

TABLE 5.—*Effect of tube diameter, velocity, and weight*

St. Joseph, Illinois, April 9, 1939

No nose

Sediment	Velocity (ft./sec.)	Weight (lb.)	Tube I. D. (inches)	Penetration (inches)	Core-length (inches)	Core-length/ penetratio
Mud—33% water	11.4	19	0.60	19.5	6.0	0.31
	11.4	21	0.82	19.0	7.5	.39
	11.4	24	1.03	18.0	9.0	.50
	11.4	23	1.37	12.5	9.2	.74
	11.4	31	2.06	13.5	11.2	.83
	11.4	37	2.44	12.0	11.5	.96
	11.4	30	3.07	10.0	9.5	.95
	19.7	19	0.60	26.5	3.5	.13
	19.7	21	0.82	30.5	11.8	.39
	19.7	24	1.03	26.0	14.2	.55
	19.7	23	1.37	20.5	14.0	.68
	19.7	31	2.06	19.0	14.0	.74
	19.7	37	2.44	17.2	15.5	.90
	19.7	30	3.07	17.0	15.5	.91
Stiff clay 34% water	11.4	31	2.06	7.8	5.2	.67
	40.0	31	2.06	15.0	9.5	.63

inches. In operations at sea, cores obtained with the 2.44-inch core-tub averaged about 25 per cent longer than those taken with the 2.06-inc tube (Table 1).

A factor affecting penetration which has often been neglected is th length of the core-tube. In order to test the effect of core-tube lengt data from all corings were plotted (Fig. 2). The diagonal line indicate the locus on which the points would lie if the instrument had penetrate just to the bottom of the weights, immersing both the core-tube and th valve in the mud. Fifty-six of the 187 points lie below this line, an also fairly close to it, suggesting that many of the penetrations wer shortened by the plunging of the weights into the mud. In order t avoid this braking effect longer core-tubes should have been used.[4]

Friction of the sediment against the inside of the core-tube is also factor controlling core-length. Cores taken in experiments using celluloi

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[4] Two tests using 30-foot core barrels were made in recent work, but unfortunately only sections 2.06 (i.d.) pipe were available. Pipe of this diameter was not strong enough to resist bending, ar consequently both trials failed.

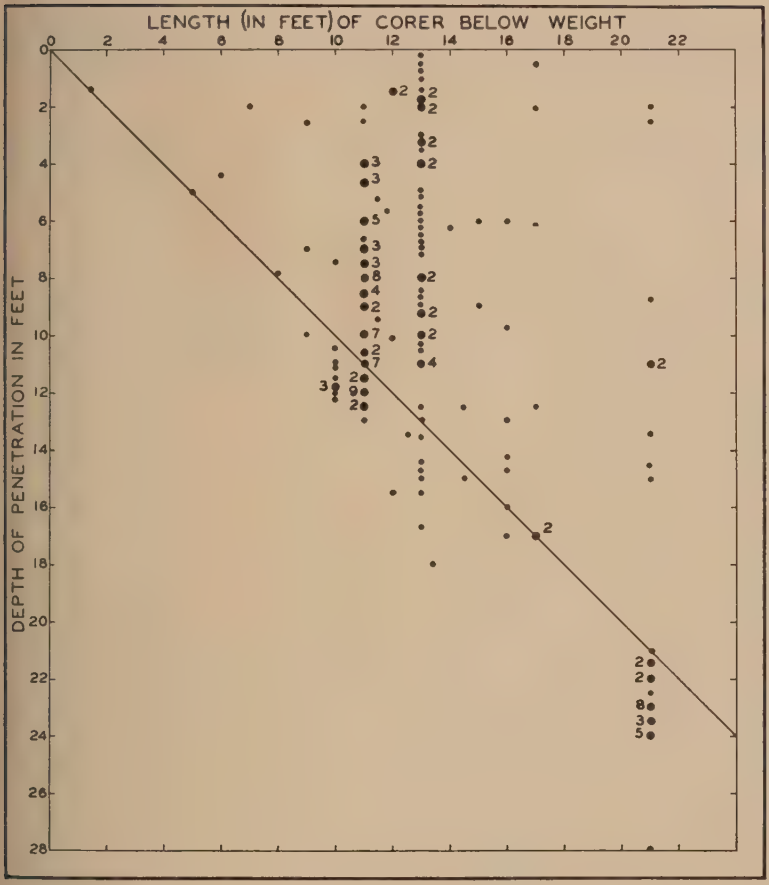

FIGURE 2.—*Effect of length of core-tube and valve housing on core-length and penetration*

Large dots and adjacent figures show position and number of coinciding tests. Braking of the weight as it plunges into the sediment retards further penetration.

ners were slightly longer than others taken in the absence of a smooth ner.

VELOCITY AND WEIGHT OF CORER

Both increased weight and increased velocity were found to be impor-ant in obtaining longer cores and deeper penetrations (Tables 1-6). The atio of core-length to penetration was usually slightly lower with higher elocities. However, cores taken by the Varney-Redwine hydraulic appa-atus as well as others taken in experiments on land with the Piggot

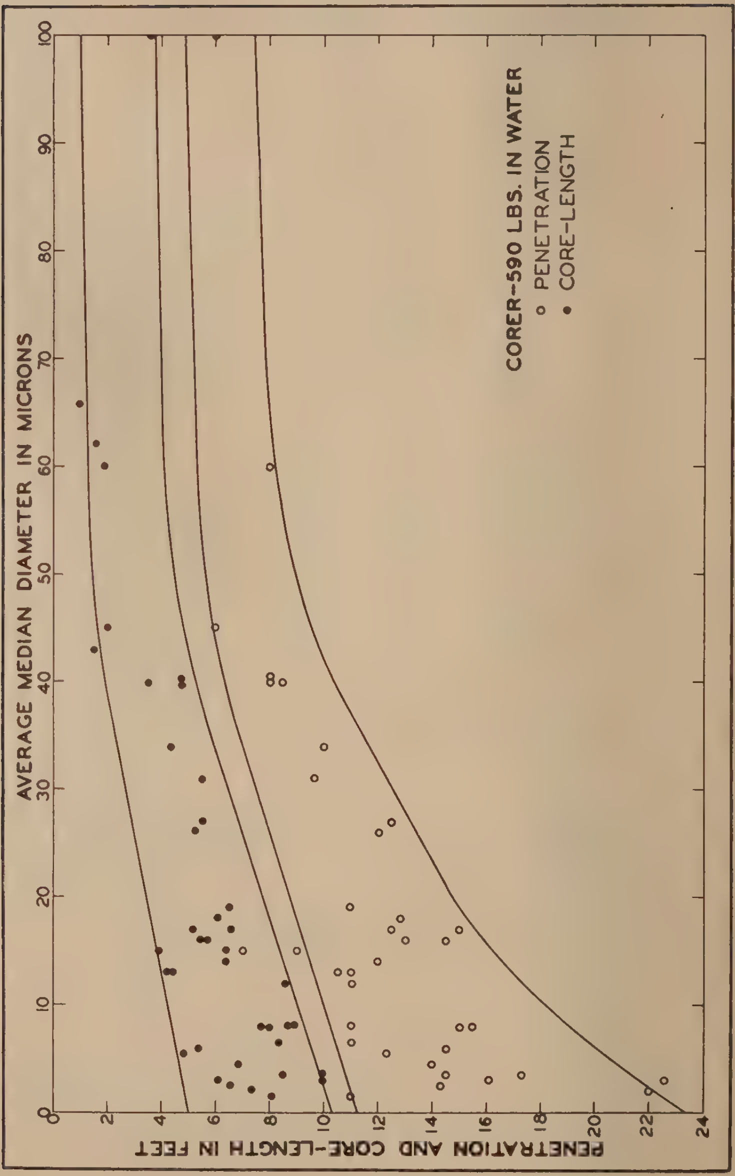

FIGURE 3.—*Effect of median diameter of sediment on core-length and penetration*

xplosive type show a similar ratio to that found in the present writers' ork (L. E. Redwine and C. S. Piggot, personal communications).

SEDIMENT CHARACTER

Study of coring data indicates that one of the most important factors ıfluencing core-length and depth of penetration is the character of the diment. Such properties as medium diameter, water content, sorting, ineralogy, and grain shape appear to be significant. Sediments encoun-ered by the Meteor Expedition, listed in the order of increasing core-ngth are: sand, diatom ooze, pteropod and globigerina ooze, hemipelagic nd glacial-marine mud, and red clay (Pratje, 1935, p. 24). Excepting iatom ooze it will be noted that longer cores were obtained from finer-rained sediments. Pratje considered diatom ooze a special case because f the feltlike texture formed by the interlocking lath-shaped grains.

TABLE 6.—*Effect of weight and velocity in coring mud*
Stream bed, St. Joseph, Illinois, April 9, 1939
No nose

Velocity (ft./sec.)	Weight	Tube I.D. (inches)	Penetration (inches)	Core-length (inches)	Core-length/ penetration
11.3	31	2.06	13.5	11.3	0.84
			13.0	11.3	.87
11.3	89	2.06	22.0	15.0	.68
19.7	31	2.06	19.0	14.0	.74
19.7	49	2.06	33.5	21.0	.63
			30.0	20.0	.67

Sediments which were sampled off California and in the Gulf of alifornia may be classified into five main groups: sand, sandy mud, lty or clayey mud, diatomaceous mud, and red clay. Table 1 shows ıat both the average core-length and the average penetration are greater r finer sediments. The ratio of core-length to penetration is also greater r finer sediments. Figure 3, based on sediment analyses made by evelle, bears out the conclusion from field data that there is at least rough correlation between the coring properties of sediments and their rain size.

The coring properties of sediment are also closely related to their water ntents. (Compare Figures 3 and 4.) In each of about a hundred cores amined, the water content was found to be lower at the bottom than t the top of the core (Fig. 5). (*See also* Bramlette and Bradley, 1940,

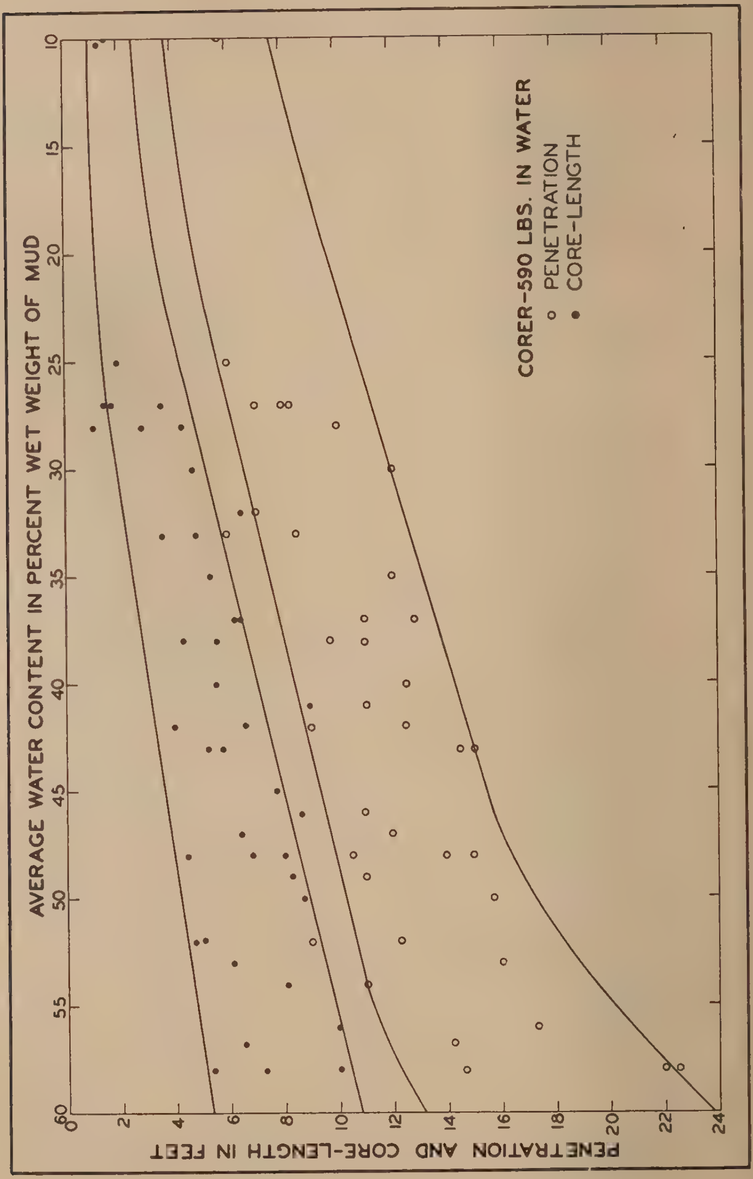

FIGURE 4.—*Effect of sediment water content on core-length and penetration*

. 27, for similar data on Atlantic cores.) The only exceptions were those ı which the sediment at the core bottom was much finer-grained than hat nearer the top of the core. This variation may be of considerable ignificance as will be pointed out later.

CORE SHORTENING

GENERAL

For most marine cores on which complete data are available, the core-ength ranges from 40 to 70 per cent of the depth of penetration. It is bvious that an understanding of the manner by which this shortening ccurs must be obtained in order to correlate layers of sediment. The ıanner of shortening also bears on the interpretation of physical prop-rties of samples at various depths in cores.

LOSS FROM CORE-TUBE

A few cases of shortening can be explained by partial loss of the sample uring or after withdrawal of the corer from the sediment. This is more ikely to occur with cores of sand than with finer sediment (Table 1); owever, careful checking of the inside of the core-tube or core-liner above ıany cores of mud showed that no slipping had occurred. Also, in a umber of the later field operations a core retainer placed in the nose Pl. 1, fig. 2) automatically closed after the core had been taken, thus reventing loss by slipping. Shortening still occurred to the same extent s when this retainer was not used.

Since the lengths of all experimental cores taken on land were measured efore withdrawal of the instrument from the sediment, the possibility of lipping was eliminated. Yet, each of about 150 such cores were shorter han the distance of penetration.

COMPACTION

It is conceivable that the shortening might be due to compaction result-ng from the escape of water (Wrath, 1936; Bramlette and Bradley, 1940, . 27). If this occurred, however, it would seem that traces of channels f escape of the water might be left in the core, but none has been noted. urthermore, laboratory experiments indicate only a slight decrease in vater content of the core over that of the undisturbed sediment. For xample, a core was taken in a box of artificially colored clay layers ıaving an original water content of 54.4 per cent by volume (Table 7). he average water content by volume for the entire core sample was 53.0 er cent; hence, the core-length should have been 97 per cent of the enetration if shortening were due only to compaction or loss of water.

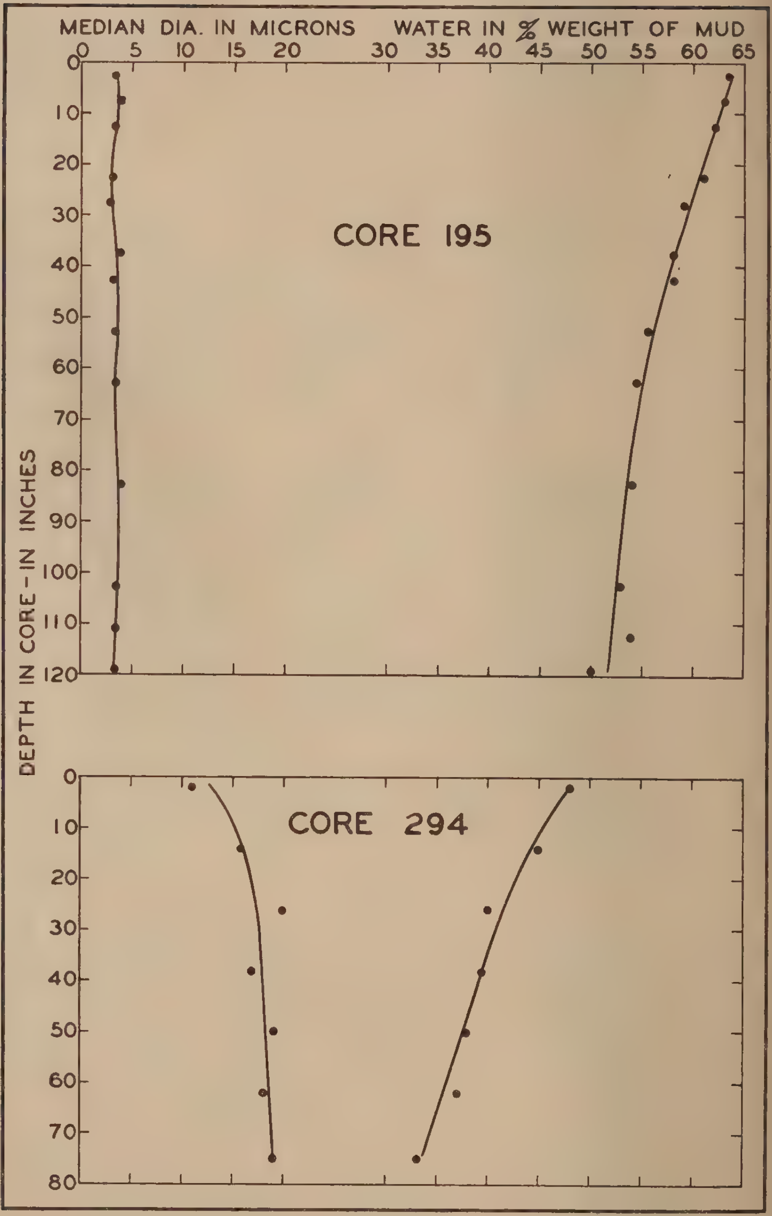

Figure 5.—*Variation of water content with depth in cores taken in field operation* Note vertical gradient of water content which exists even though grain-size is relatively constant.

Actually, the core-length was only 30 per cent of the penetration; therefore, some other factor was much more important than compaction.

The idea has sometimes been expressed that the shortening is due to compression. However, this is obviously a loose use of the word *compression* (change in volume of a given mass in response to pressure) in place of *compaction* (change in volume due to loss of water).

TABLE 7.—*Water content of core taken through layers of colored clay of equal water content*

August 28, 1938

Depth in core (inches)	Depth of penetration (inches)	% wet weight	Water content % wet volume
0–1	0–1	32.3	54.4
1–2	1–2	31.2	53.2
2–3.4	2–11.4	29.9	51.8

SLUMPING WITHIN CORE-TUBE

Hvorslev (personal communication) has found that slumping or lateral expansion of soft material until it fills the core-tube is a factor causing shortening of soil samples. Probably some of the difference between the depth of penetration and the length of sea-floor cores is due to the same cause. When the inner diameter of the nose is 1.87 inches and that of the core liner is 2.02 inches, complete slumping would reduce a core to 86% of its original length. Similarly, the 2.06 inch nose with the 2.40 inch core liner would produce a core 74% as long as the original. Judging by the fact that core-length to penetration ratios average about 50% (Table 1), slumping is not the major cause of the shortening. Note also that the core-length to penetration ratio is low even when no nose is used and no opportunity to slump is presented (Figs. 7-10; Tables 2, 3, 5, 6).

REPRESENTATION OF ONLY TOP LAYERS OF SEDIMENT

Core samples are usually interpreted as though they consisted of only the undeformed top layers of sediment penetrated (Schott, 1935; Bramlette and Bradley, 1940). However, if this were true, it would follow that the inside of the core-tube exerts absolutely no resistance to the passage of a cylinder of mud until the core reaches a certain length, after which the resistance instantaneously becomes so great that the core cannot be pushed farther up the tube.

In order to learn something of the manner by which this internal resistance is built up, experiments were made in mud using a 2.06-inch (i.d.) core-tube. It was found that the length of the core could be increased by withdrawing the tube from the mud and, without removing the core dropping it back again. Increments were added for each of 11 trials, a the end of which the total core was twice the length of the original and nearly twice the average depth of the individual penetrations (Fig. 6) While not directly comparable to actual coring processes, this experiment shows that resistance toward movement of the core becomes gradually and not suddenly greater as the core becomes longer. Thus it seems impossible that there could exist a stage of no resistance during which the core would be taken, followed by a stage of high resistance when no more core could enter the tube.

REPRESENTATION OF ALL LAYERS PENETRATED

General.—As pointed out by Hvorslev (1940, p. 17) and as shown in Figure 6, a point may be reached where the resistance toward movement of a core becomes so great that further penetration causes only a pushing aside of sediment at the core-nose. There is some question, however whether this point is reached during the course of ordinary coring operations.

It is obvious as shown above that increments must still be added to the core after the instrument has penetrated the sediment to a depth greater than the length of the core. However, for the proper interpretation of core samples, it is necessary to know whether there are new core increments throughout part of the remaining distance of penetration or throughout all of it. Similarly, it is desirable to know something of the relative size of the increments added to different portions of the core. Both of these problems were investigated by a number of methods.

Coring in layered sediment.—The problem of shortening may be solved by a comparison of layers in the core with the same layers in the undisturbed material. In the absence of Recent varved clays, some experiments were made in crudely stratified material consisting of 16 inches of mud at the top, 20 inches of mud high in organic debris in the middle, and cleanly washed sand at the bottom. All cores penetrating a given layer contained some material from that layer even though the core-length itself were less than the depth of burial of the top of the layer. Variation in the coring properties of the different layers prevented the making of interpretations regarding the size of increments added to the core during the penetration.

Less comparable to actual coring operations, but still significant, is a series of experiments in which weighted glass tubes of 0.59-inch inner diameter were dropped into a box of layered clay having a uniform water content. Eleven artificially colored clay layers, each one inch thick, were resent. Of 53 cores in which no observed loss had occurred only 6 failed) include the layer in which the tip of the corer had stopped. Since ıe average penetration into this layer was only 0.24 inch, the absence of

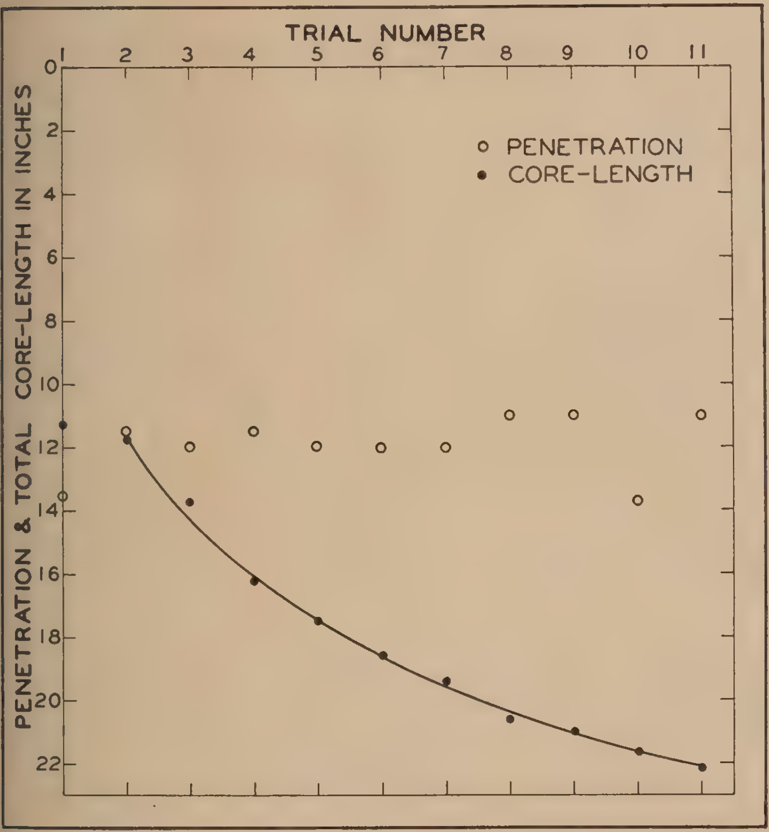

FIGURE 6.—*Experiment showing gradual increase in wall friction*

A 206-inch I.D. core-tube was dropped into mud 11 times from same height. After each trial, core was measured but not removed from tube. Note effect or total core length on size of increments. Experiment at St. Joseph, Illinois, stream channel, April 9, 1939.

ıe bottom layer may have been due to very slight slipping of the core hen the tube was extracted or, more likely, to down-bending of the layers ightly in advance of the corer. In these small scale cores, the top layer as represented in its full thickness, and each successive lower layer was rogressively thinner (Fig. 7) so that the average core-length was only 0% of the penetration.

Hammering investigation.—While a core-tube is being hammered c pushed into sediments the length of the core and the distance of penetration may be measured at frequent intervals. A test using this metho was made on a tidal flat, where three cores were taken with penetration

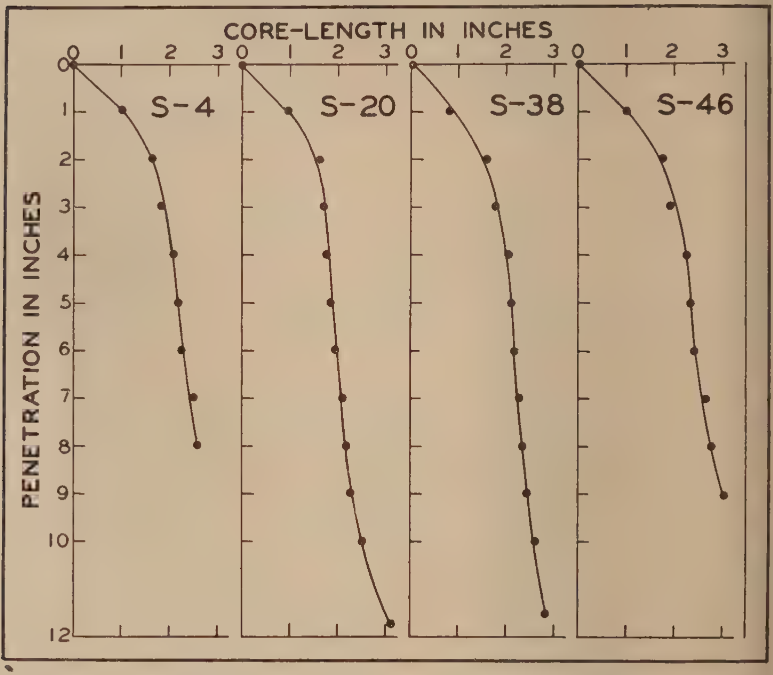

FIGURE 7.—*Core-length vs. penetration curve obtained by dropping small-scale corers into layered clay*

Note that smaller increments are added as core becomes longer. No nose. August 28, 1938.

of 7 to 8 feet. Two thin-wall 2-inch (1.91 in. I.D.; 2.02 in. O.D.) pipes without noses and one standard 2-inch (2.06 in. I.D.; 2.38 in. O.D.) pip equipped with a nose (1.88 in. I.D.) were hammered into mud. Examination of Figure 8 shows that increments of approximately the same siz were added to the cores along the entire distance of penetration in spit of the variable nature of the sediment.

On the other hand, in a similar test which consisted of hammering 45 mm. diameter core-tube into mud, Pratje (1934) found evidence a lack of continuous addition of core increments toward the bottom of th penetration. The sediments involved, however, seem to be unusual i

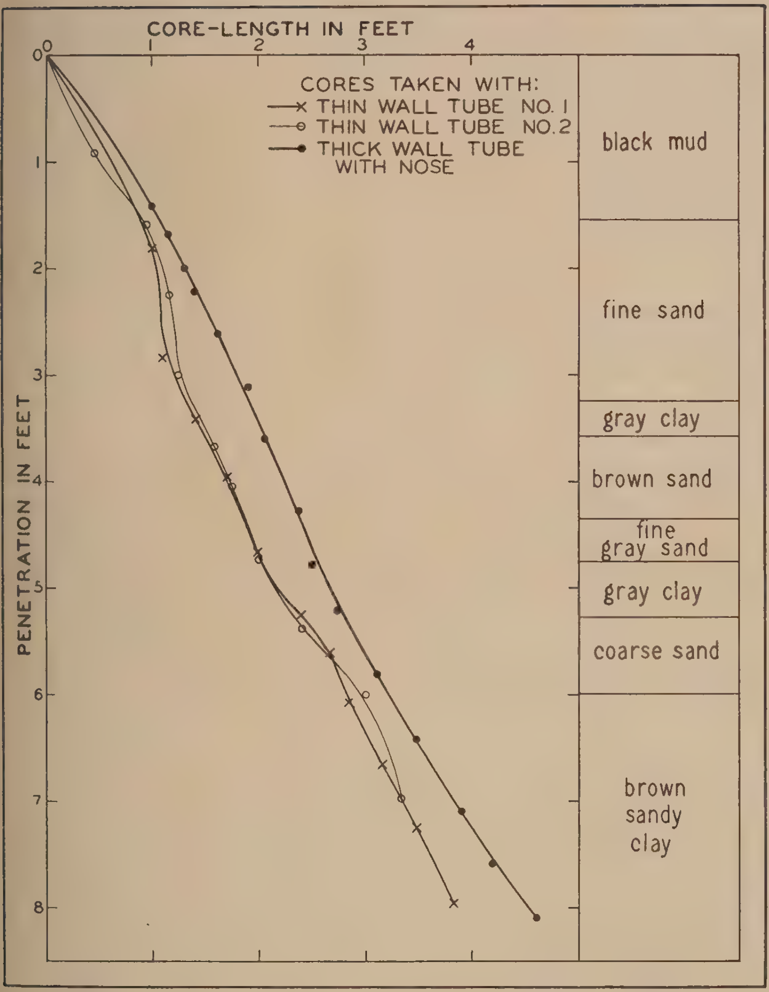

FIGURE 8.—*Core-length vs. penetration curve obtained by hammering core-tubes into sediment*

Note that cores taken with thin wall tubes, having no nose attached, were more influenced by sediment character than those with thick wall tube, equipped with a nose. October 1938.

that the water content ranged progressively from 51% at the surface to 68% at a depth of 4 meters. This variation suggests that the deeper material was more mobile and thus could be easily pushed aside at the core-nose.

Photographic study.—A photographic method of comparing core-lengt with penetration was attempted in an effort to learn something of corin mechanics while experimenting under conditions similar to those of actua coring operations. A light rod with a foot, or pad, at the lower end an a cross-piece at the upper end was placed inside a 2.06 in. I.D. core-tube The rod was just the length of the core-tube, and in the starting positio the cross-piece rested on top of the vertical tube. When the core-tub was dropped into mud, the bottom of the rod remained on the surface o the mud core; accordingly, the length of rod extending above the core-tube could be used as a measure of the length of the core. Similarly, th length of the core-tube projecting above the ground surface could b employed as a measure of the depth of penetration. By use of a movi camera, the positions of the core-tube and of the cross-piece of the ro were photographed at short time intervals. Later, the images wer measured on a screen on which the film was projected.

Five experiments, made with a relatively light apparatus on a tidal fla near San Diego, California, were photographed in this manner. In tw of these cores, increments were added along the entire distance of penetration. In one experiment, however, apparently no core was added i the last 10 per cent of the penetration. In the two other trials the apparent length of the core decreased at the bottom of the penetration, probably because the rod drove down into the top of the core. The dat from these experiments are shown in Figure 9. It will be noted that except near the bottom, equal increments were added per unit of penetration and not smaller increments as in the small-scale experiments with th glass tubes.

Two other cores, 4 feet long with penetrations of about 7 feet, wer taken near the site of the previous experiments, using a much heavie instrument. In both of these tests the ratio of core-length to penetratio remained nearly constant throughout the length of the core, but the penetration per unit of time and likewise the core recovery gradually decrease to zero during the last quarter of the coring time interval (Fig. 10). I should be noted, however, that the velocity of the apparatus (penetratio per unit of time) actually increased for the first 0.4 of a second becaus of the excess of gravitational acceleration over the resistance offered b the mud. In this respect the conditions of the experiment were not quit analogous to those of actual coring operations.

Sea-floor experiments.—The above data were derived from experiment made on land; therefore, it became desirable to obtain similar informatio for cores taken at sea. A relatively simple device for measuring and recording the core-length and penetration at a number of points for eac ore was constructed (Fig. 11). Essentially, it consists of a core-tube, a lunger, and a rider. The tube is a 2.06-inch pipe with a ⅛-inch slot nilled down one side. The opposite side has screw heads mounted on the utside at 4-inch intervals. The plunger is a cylindrical paraffin-coated stick with disk guides at each end to center it in the tube and permit it to slide freely inside. Fitted to slide along the outside of the tube is a rider so constructed that contact with each screw head of the tube causes a pointer extending through the slot of the tube to cut momentarily into the paraffin coating of the plunger.

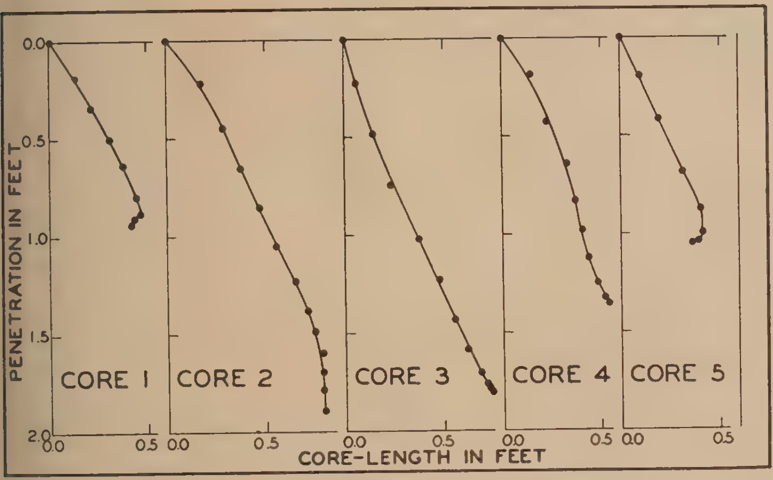

Figure 9.—*Results of photographic study of five short cores*

Experiments at Mission Bay, California, using 30- to 80-pound 2.06-inch I.D. core-tube dropped from a height of 3 to 5 feet. Each dot represents a photographic exposure. No nose. August 1939.

In operation, the instrument was dropped slowly to the bottom. While the tube drove down into the mud, the rider stopped at the mud surface, and the plunger remained just above the core. Each screw head of the tube as it passed through the rider caused a notch to be cut in the plunger. If the plunger itself were stationary with respect to the core-tube (that is if no core were taken) the notches in the paraffin would be 4 inches apart. On the other hand, if the core rose inside the tube as rapidly as the tube penetrated the mud (because of no shortening) all the notches would be superimposed. Accordingly, successive notches in the paraffin indicate 4-inch increments of penetration, and the distance between them is equal to the difference between the increment of penetration, 4 inches, and the increment of core. Thus, measurement of the distances between the

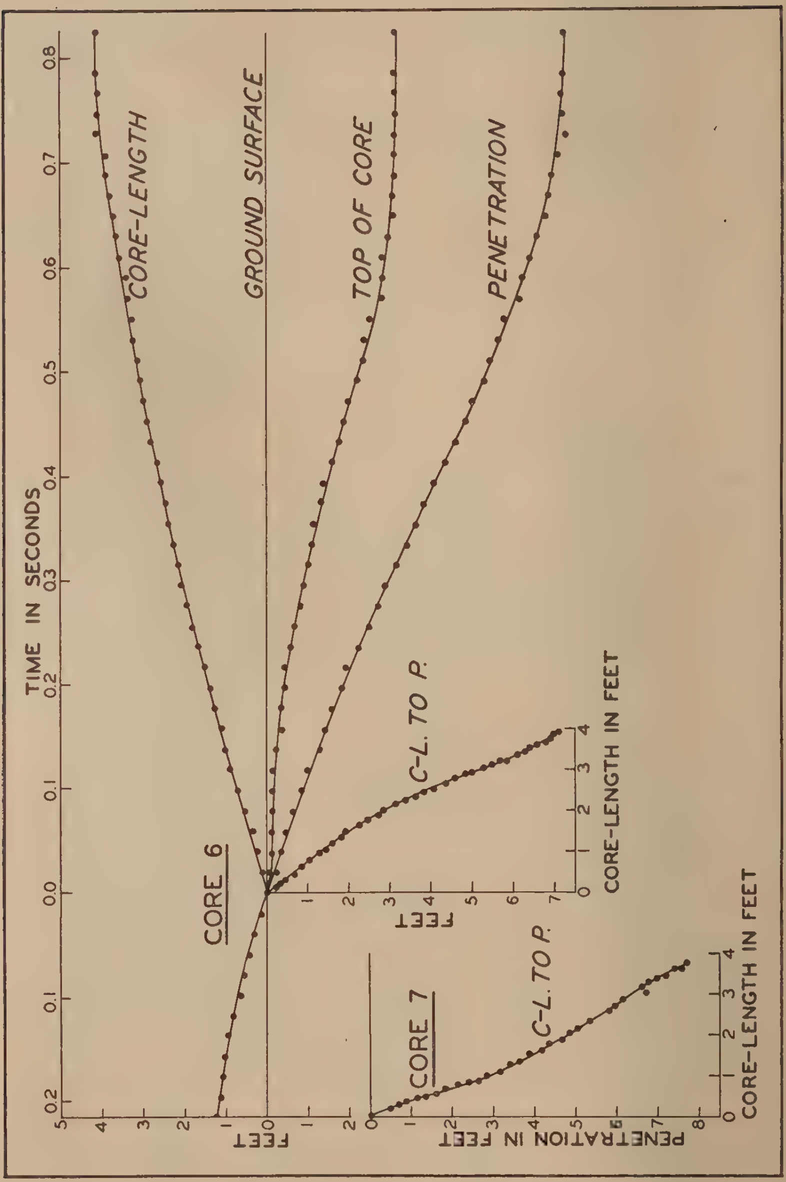

FIGURE 10.—*Results of photographic study of two long cores*

Experiments at Mission Bay, California, March 16, 1940, using 170-pound 2.06-inch I.D. corer dropped from a height of 1.2 and 1.8 feet. No nose.

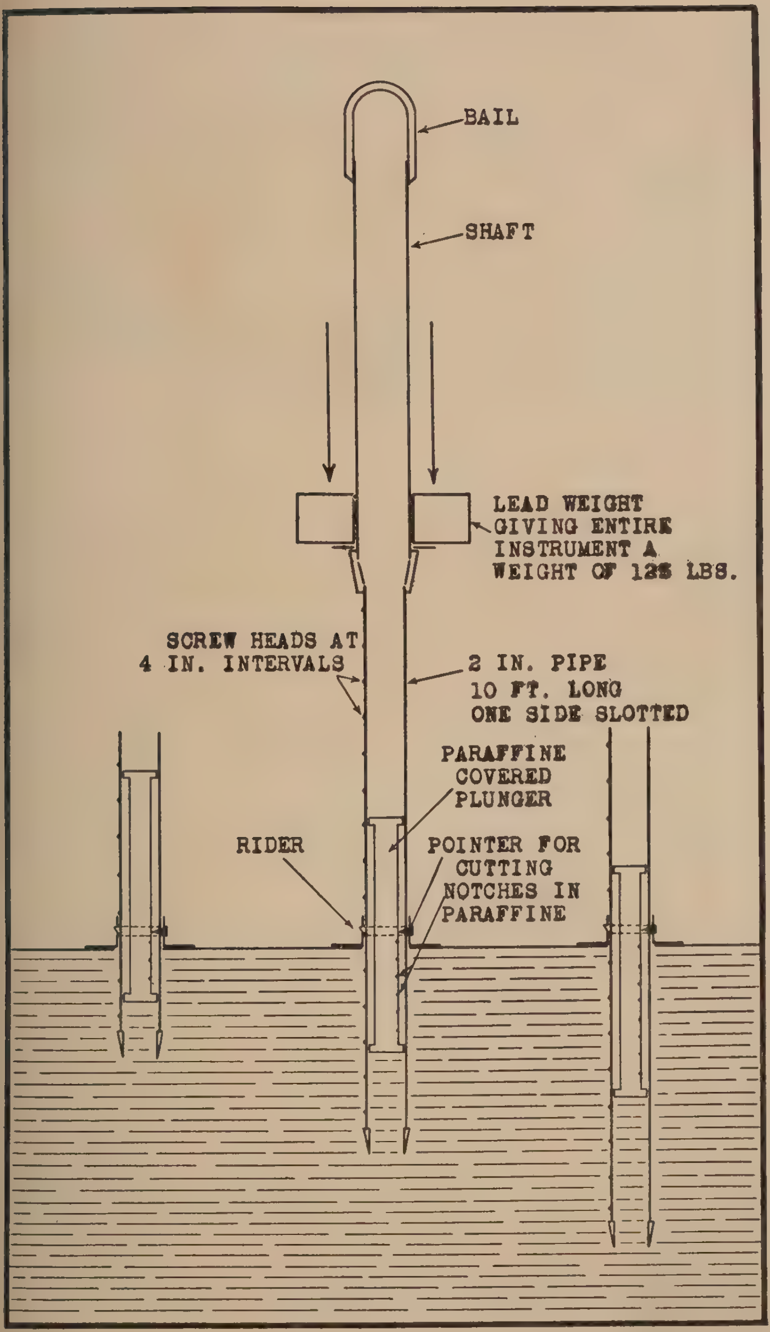
BAIL
SHAFT
LEAD WEIGHT
GIVING ENTIRE
INSTRUMENT A
WEIGHT OF 125 LBS.
SCREW HEADS AT
4 IN. INTERVALS
2 IN. PIPE
10 FT. LONG
ONE SIDE SLOTTED
PARAFFINE
COVERED
PLUNGER
RIDER
POINTER FOR
CUTTING
NOTCHES IN
PARAFFINE

FIGURE 11.—*Device for measuring core-length and penetration during process of coring sea-floor sediments*

Three successive stages are shown.

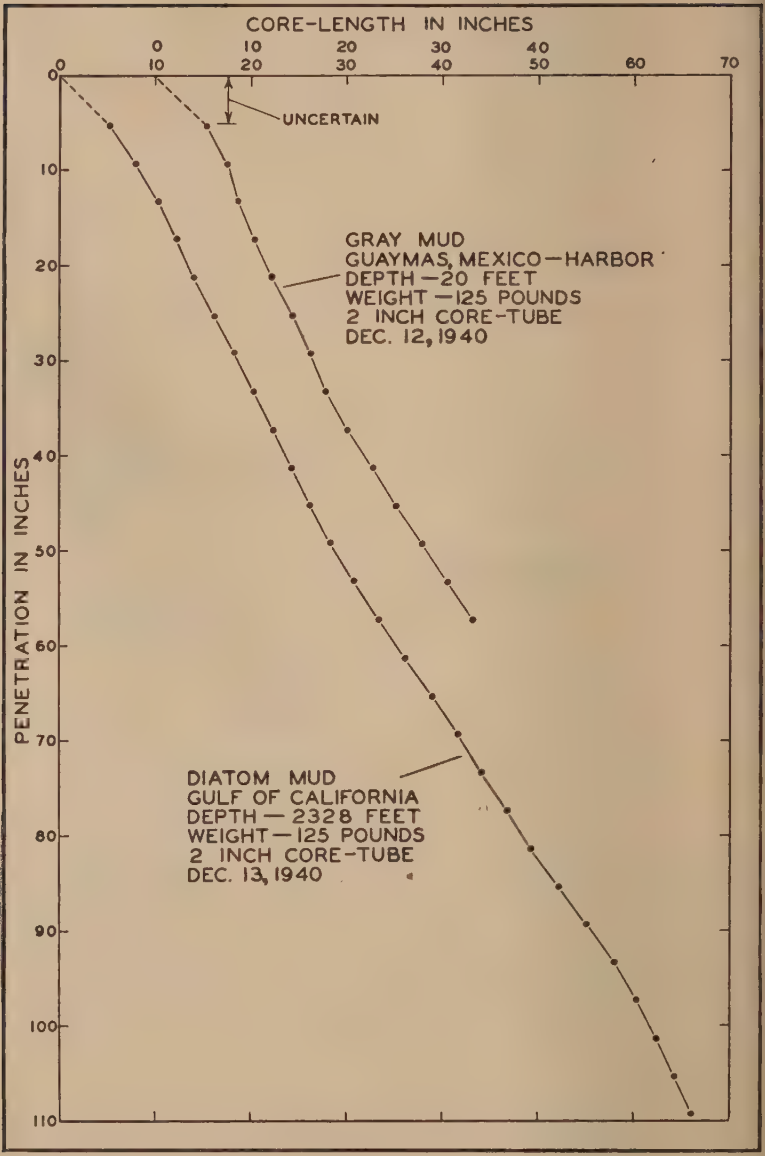

FIGURE 12.—*Core-length vs. penetration curve obtained under field coring conditions*

Nose attached. December 12 and 13, 1940, Gulf of California.

tches of the plunger provides enough information for the construction a core-length to penetration curve.

The instrument was used in gray mud in Guaymas Harbor, Mexico, a depth of 20 feet. This trial resulted in a 33-inch core with a 57-h penetration. Figure 12 shows that the core-length to penetration io was essentially constant throughout the process of coring.

An even more conclusive result was obtained in diatomaceous mud at epth of 2400 feet. The resulting core was 66 inches long with a penetion of 119 inches. Data on core-length and penetration at 27 points re obtained (Fig. 12) showing very clearly the presence of nearly equal rements of core per unit of penetration throughout the entire distance penetration.

INTERPRETATION OF EXPERIMENTAL RESULTS

n the coring experiments, it was observed that lengthening of the core tinued throughout the entire distance of penetration except in a few tances in which the limitations of experimental methods were apparent. e length of increments per unit of penetration, however, was dependent the sediment cored. Small-scale experiments made in clay having the ne water content at all depths showed that the core increments became aller as the core became longer. On the other hand, experiments in d, which had been deposited recently by natural agencies, showed that rements of approximately the same size were added to the core per t of penetration regardless of the length of the core or the depth of etration. In normal muds like those in which the latter experiments e made, the water content decreases with depth of burial when the in size remains constant. The difference in behavior may be understood ter by briefly reviewing the process by which cores are taken.

As the corer strikes the sediment surface, it has a certain amount of etic energy. This energy is expended in overcoming outside wall fric- of the tube, friction between the mud core and the inside wall of tube, and resistance of the mud toward being pushed aside or down ped at the lower end of the tube. While the core is short, it offers le resistance toward being pushed farther into the tube. As the same e, however, the mud at the nose is easily pushed aside or down warped that only part of it enters the tube. When the core becomes longer, re force is required to push it against the increased frictional resistance. rder for equal increments to be added to the core at depth, the resist- e of the mud against being pushed aside or down warped must also ease.

n a mud having uniform plasticity (as indicated by uniform water tent and grain-size) the resistance of layers toward being down warped

and thinned increases only slightly with depth; and accordingly, small
increments are added to the cores as they become longer. An example
this type of shortening is given by the small-scale cores taken in the bo
of colored clay layers (Fig. 7). A similar type of shortening has bee
reported in the case of a core tube driven into Pleistocene varved sed
ments (Piggot, C. S., personal communication). Although no data as
water content or grain size of the latter sediment are available, it
probable that the material is reasonably uniform with depth since it
not being deposited at present. Similarly, experimental cores taken b
Pratje definitely showed a decrease in size of core increments with i
creasing depth of penetration (Pratje, 1934). In this instance, the wat
content was found to range from 50% at the mud surface to 68% at th
bottom of the cores. Because of this very considerable increase in wat
content, the mud at depth may have been less viscous than the surfa
mud and thus may have offered less resistance toward being pushed asi
or downwarped by the partly filled core-tube.

Ordinarily, the mud toward the bottom of the penetration is not
easily downwarped as is the mud near the surface because the lower wat
content of the former gives less lubrication for movement, i.e., is mo
viscous. Apparently this factor is sufficient to balance the increase
friction between the core and the tube, and therefore all increments add
to the core are about the same size per unit of penetration. Thus in th
seven photographic experiments and the two others made under wate
the length of the core at any instant was found to be approximately
direct proportion to the depth of penetration at that instant (Figs.
10, 12).

The mechanical pushing aside or downwarping of part of the sedime
near the nose of the instrument is usually not sufficient to destroy lamin
(Pl. 2, fig. 2). However, interesting injections of material have be
observed at boundaries between different types of sediment. Wrath r
ports similar contamination in some experimental cores (1936). Fricti
of the tube wall against mud cores produces a layer of smeared materi
generally not more than about 1/32 inch thick, and in several cores
thin that it failed to conceal the presence of thin laminations in the co

RELATION OF SHORTENING TO STUDY OF CORE SAMPLES

The linear relationship between the position of a sample in a core a
the depth at which it lay in the undisturbed sediment (Figs. 8-10, 12)
important in the interpretation of marine cores. For example, if tot
penetration is 8 feet and a core is 4 feet in length, a sample lying at
depth of 3 feet in the core should be considered as occurring at a dep

6 feet in the undisturbed sediment. The significance of such a rela-
onship is readily apparent in the calculation of the rate of deposition
sediment based on the depth in cores at which changes in types of
diment or changes in fauna occur.

As an illustration, Schott found that in seven red-clay cores taken in
e equatorial Atlantic Ocean a faunal change occurred which could be
rrelated with the end of the glacial period (Schott, 1935, p. 120-130).
suming that this faunal change, which occurred at an average depth
17.14 cm. in the seven cores, took place about 20,000 years ago, Schott
is able to derive an average rate of deposition for the red clay amount-
to 0.86 cm. per 1000 years. However, no allowance was made for
ortening. According to Pratje (1935, p. 25), the average ratio of core-
igth to penetration for the Meteor red clay cores was 59.4%. If core-
ortening occurred in a manner similar to that shown in Figures 8, 9,
, and 12, the average rate of deposition for the red clays examined by
hott is probably more nearly 1.45 cm. in 1000 years; 1.45 cm. at
ist represents a maximum rate and 0.86 cm. a minimum for these cores.

Interpretations of cores taken by Piggot across the North Atlantic
ramlette and Bradley, 1940) may also be greatly influenced by the
inner in which shortening is assumed to occur. No exact data concern-
depths of penetration have been published. Quite different pictures
the relative lengths of time represented by the alternating layers of
cial-marine deposits and foraminiferal ooze would be obtained, depend-
on whether shortening occurred in the manner shown in Figure 7 or
Figures 8, 9, 10, 12. The latter type of shortening seems far more
bable.

SUMMARY AND CONCLUSIONS

A large coring device which derives its energy from its weight and the
ocity with which it strikes bottom was developed for investigations of
marine geology. The apparatus consists essentially of a shaft on
ich is mounted a streamlined mass of lead; a valve which permits only
ward passage of water within the device; and a core-tube which retains
ore after being pushed into the bottom sediment.

The corer has been used successfully in depths as great as 12,200 feet.
iny of the cores obtained are far longer than those taken by any other
e. Cores in fine-grained sediments range up to 16 feet 9 inches in
gth and average 6 feet 3 inches. Sand was found more difficult to core.
npling was not confined to sediments, however, since small rock chips
pebbles were recovered in a number of cores.

It was observed that the core-length varied from 40 to 70 per cent of
depth of penetration. However, coring in layered sediments, measure-

ments made while the corer was being hammered or pushed into mu
photographic studies of the process of coring, and finally sea-floor e
periments showed that the core becomes longer throughout the enti
period of penetration. For tests in mud having a normal decrease in wat
content with depth of burial, the increments added to the core per un
of penetration are nearly equal throughout the entire penetration. Oth
experiments indicate that this shortening is not due to compaction
squeezing of water from the sediments but that only part of each lay
of sediment is added to the core while the remainder of the layer is push
aside. Although with continued increase in length a core will final
become so long that it acts as a solid rod and pushes all the material
the lower layers aside, experiments show that such a length is great
than those obtained in the present writers' coring operations.

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VALUES OF MILLS' RATIO OF AREA TO BOUNDING ORDINATE AND OF THE NORMAL PROBABILITY INTEGRAL FOR LARGE VALUES OF THE ARGUMENT

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A pair of simple inequalities is proved which constitute upper and lower bounds for the ratio R_x[1], valid for $x > 0$. The writer has failed to encounter these inequalities in the literature, hence it seems worthwhile to present them for whatever value they may have.

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[1] J. P. Mills, "Table of ratio: area to bounding ordinate, for any portion of the normal curve." *Biometrika Vol. 18* (1926) pp. 395–400. Also Pearson's tables, Part II, Table III.

The function R_x is defined by

$$R_x = e^{x^2/2} \int_x^\infty e^{-t^2/2}\, dt. \tag{1}$$

The following relations between $R = R_x$ and its derivatives are easily established by direct differentiations and substitutions:

$$\frac{dR}{dx} = xR - 1, \tag{2}$$

$$\frac{d^2R}{dx^2} = x\frac{dR}{dx} + R = \frac{x^2+1}{x}\frac{dR}{dx} + \frac{1}{x}, \tag{3}$$

$$\frac{d^3R}{dx^3} = \left(1 + \frac{2}{x^2+1}\right)x\frac{d^2R}{dx^2} - \frac{2}{x^2+1}. \tag{4}$$

Also by ordinary rules

$$R_x > 0, \tag{5}$$

$$\lim_{x\to\infty} xR_x = 1. \tag{6}$$

1°. Suppose that at any point $x_1 > 0$, $x_1R > 1$. Then by (2) $dR/dx > 0$, and R_x would continue to increase with increasing x: still more, xR_x would continue to increase, hence we should have $xR_x > 1$ for $x \geqq x_1$, which contradicts (6). Therefore we find $xR_x \leqq 1$ for $x > 0$, and

$$R_x \leqq \frac{1}{x}, \tag{7}$$

which establishes the required upper inequality.

2°. Suppose that at any point $x_2 > 0$, $d^2R/dx^2 < 0$. Then by (4) $d^3R/dx^3 = (d/dx)(d^2R/dx^2) < 0$ at this point. Since these derivatives are continuous this implies that for all $x > x_2$, $d^2R/dx^2 < [d^2R/dx^2]_{x=x_2} < 0$. Then we get the inequalities, for $x > x_2$

$$\frac{dR}{dx} < \left[\frac{dR}{dx}\right]_2 + (x - x_2)\left[\frac{d^2R}{dx^2}\right]_2 < \left[\frac{dR}{dx}\right]_2$$

$$R < R_{x_2} + (x - x_2)\left[\frac{dR}{dx}\right]_2 + \tfrac{1}{2}(x - x_2)^2\left[\frac{d^2R}{dx^2}\right]_2$$

where $[\ ]_2$ indicates evaluation at $x = x_2$. Since $[d^2R/dx^2]_2 < 0$, this implies that for sufficiently large x, $R_x < 0$, which contradicts (5). It follows then that (3) is positive, and substitution of (2) gives

$$R_x \geqq \frac{x}{x^2+1}. \tag{8}$$

We combine (7) and (8) in the double inequality:

$$\frac{x}{x^2+1} \leqq R_x \leqq \frac{1}{x}, \qquad \text{if } x \geqq 0. \tag{9}$$

This gives for the probability integral the corresponding inequality

$$\frac{x}{x^2+1} \cdot \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \leqq \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2}\, dt \leqq \frac{1}{x} \cdot \frac{1}{\sqrt{2\pi}} e^{-x^2/2}. \tag{10}$$

It can easily be shown (for $x > 0$) that equalities in (9) and (10) are impossible.

Contribution No. 150

APPARATUS FOR COLLECTING WATER SAMPLES FROM DIFFERENT DEPTHS FOR BACTERIOLOGICAL ANALYSIS[1]

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Prerequisite to quantitative studies on the occurrence and importance of bacteria in the sea or other natural waters is a satisfactory device for collecting water samples for bacteriological analysis from any desired depth. Such a device must be easily sterilized, susceptible to aseptic manipulation under the most rigorous field conditions, possible to operate at high hydrostatic pressures and it must be made of biologically inert materials. It is desirable that the bacteriological water sampler can be used on the standard hydrographic or sounding wire in tandem or multiple units to provide for the simultaneous collection of samples from different depths and in conjunction with Nansen, Ekman, or Allen bottles, reversing thermometers or other hydrographic apparatus on the same wire. Sturdiness of construction, convenience of operation and economy of manufacture are also important features.

A survey of the literature reveals that more than a hundred bacteriological water samplers have been described introducing new

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[1] Assistance in the preparation of these materials was furnished by the personnel of Work Projects Administration Official Project No. 65-1-07-2317.

[2] Contribution new series No. 150.

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principles or modifications, but they all have limitations which restrict their usefulness. Unfortunately the data obtained from the bacteriological analysis of water collected with many samplers are open to criticism or are of only historical significance because the containers could not be sterilized, they were subjected to possibilities of extraneous contamination or they were made of metals which exert a bactericidal effect. The majority of the samplers which have been described are suitable only for collecting surface samples or samples from shallow depths. Others are unreliable, excessively expensive, intricately complicated or otherwise unsatisfactory. The apparatus which is described below has given good results under various conditions, it is simple to construct and it is positive in operation at any depth.

HISTORICAL

Besides the numerous methods which have been described for collecting water samples from the surface, three different types of samplers have been used: (1) weighted glass bottle from which the stopper is removed by a string, spring or messenger at the desired depth, (2) cylinder to which water is admitted by opening valves or by withdrawing a piston and (3) partially evacuated glass receptacle to which water is admitted by breaking a capillary glass tube.

Johnston (1892), Heydenreich (1899), Abbott (1921), Whipple (1927), Zillig (1929), Eyre (1930) and others have described ingenious devices for removing the stopper from a sterile bottle after it has been lowered into the water. However, it is obvious that the operation of such samplers is restricted to relatively shallow depths because the hydrostatic pressure at greater depths prevents the removal of stoppers from empty bottles. (The hydrostatic pressure of water increases approximately one atmosphere, or 15 lbs. per square inch, for each ten meters of depth.) In fact, unless provisions are made to prevent their descent, rubber stoppers will be pushed into the bottle at 50 to 100 meters and eschewing this, the empty bottles will be crushed at depths of a few hundred meters.

Otto and Neumann (1904) collected samples in a metal cylinder the ends of which could be closed with rubber gaskets at the desired depth. A nickel-plated cylinder with cocks operated by a messenger was used by Bertel (1911). However, it is objectionable to send such a cylinder down open because it might become contaminated with extraneous material while descending through the water and it is virtually impossible to perfect leak-proof valves or cocks which operate with sufficient ease to permit a pressure-resistant cylinder to be sent down empty. Matthews (1913) sought to obviate this difficulty by filling a glass-lined cylinder with 95 per cent alcohol which provided for the sterility of the apparatus as well as for the equalization of pressure. One messenger was dropped to open the ends of the cylinder thus permitting the disinfectant to diffuse out, after which a second messenger closed the valves to entrap a water sample from the desired depth. Drew (1914) used this apparatus with expressed confidence to depths of 800 meters. Others have used it with phenol solution or other disinfectants. Besides the expense and inconvenience of operating this apparatus there is always a possibility of the disinfectant diffusing out prematurely through a faulty valve, or all of the disinfectant may not be washed out during the time the valves are opened and closed.

Young, Finn and Bedford (1931) fitted a phosphor-bronze cylinder with a brass piston which is withdrawn by a messenger-activated mechanism thereby aspirating a water sample. In order to eliminate the bactericidal effect of metals, Renn (unpublished) used a large ground-glass cylinder fitted with a solid ground-glass piston or plunger. It is doubtful, though, if such cylinder and piston arrangements can be made so that they are absolutely leak proof at great depths and it is especially difficult to exclude water from the orifice until the messenger is dropped. Unless it is closed right to the end, the orifice may admit a small amount of surface water which will be aspirated when the piston is withdrawn. This objection applies to Reyniers' (1932) glass cylinder which is ingeniously opened and closed by flexible rubber tubing.

Russell (1892) applied the unpublished evacuated glass-bulb capillary-tube idea of Massea by fitting a small flask with a glass tube the end of which was sealed hermetically. Provisions were made for breaking the end off the glass tube with a messenger thus permitting the ingress of water. Modifications of this capillary tube idea have been described, in most cases independently, by Praum (1901), Miquel and Cambier (1902), Portier and Richard (1906), Druse (1908), Parsons (1911) and Issatschenko (1914). In its most practical form Wilson (1920) used a large test tube fitted by means of a rubber stopper with a capillary glass tube the end of which is sheared off by a lever activated by a messenger. Gee (1932) attached it to an Ekman bottle, provided a long capillary tube to retard the sudden inrush of water when the tip was broken at great depths and used a thick-walled test tube with the neck constricted to prevent the descent of the rubber stopper into the test tube with increasing pressure. ZoBell and Feltham (1934) bent the glass inlet tube in such a way that it was broken at a point remote from possibilities of contamination by the messenger and simplified the breaking mechanism.

BACTERICIDAL EFFECT OF METALS

Alloys of copper, lead, nickel, silver, tin, zinc or other metals lend themselves readily to the manufacture of water sampling apparatus but it has been recognized for many years that all except the noblest metals have an oligodynamic effect (Raadsveld, 1934). After finding a reduction of 97 to 100 per cent in the bacterial population in 100 ml. quantities of sea water exposed to 2 square inches of bronze, nickel, brass and other alloys, Drew (1914) concluded that platinum is the only metal suitable for the interior of bacteriological water sampling apparatus. According to Bedford (1931) the bactericidal effect of the bronze and brass sampling bottle of Young et al. (1931) was inappreciable in sixty minutes but noticeable in ninety minutes.

Observations made at the S. I. O. during the last decade indicate that the less noble metals have a pronounced effect on the survival and activity of bacteria in samples of sea water. Under certain conditions most of the bacteria in sea water are killed within a few minutes when in contact with bright brass, bronze or other alloys containing copper, nickel, tin or zinc. Sea water itself stored in brass receptacles for a few hours becomes bacteriostatic for some bacteria although it enhances the growth of other bacteria. It is beyond the scope of this paper to consider the factors which influence the oligodynamic effect of heavy metals on the activity of bacteria in sea water but a few experiments will be summarized to show that metal containers for bacteriological water samples should be shunned.

Investigators on several oceanographic expeditions have analyzed bacteriologically water samples collected with Nansen, Ekman or other metal bottles. As a rule they observe that in spite of the fact that the bottles were not sterilized, few or no bacteria could be demonstrated in the water. Such observations have been interpreted as indicating that there are few or no bacteria in the sea. That such an interpretation is not always valid is proved by the data recorded in Table I which gives a protocol of a series of experiments in which sea water was stored in Nansen bottles.

Thoroughly cleaned Nansen bottles were filled with raw sea water. After different periods of storage at 22° C. samples were withdrawn for bacteriological analysis. Control water samples were stored in glass bottles for the same time. The bacterial population was determined by plating procedures using nutrient sea water agar (ZoBell, 1941). It will be observed from Table I that whereas the number of bacteria in the control sea water in glass containers decreased slightly with storage and then started to increase, the bacteria rapidly disappeared from the sea water which was stored in Nansen bottles for a few hours.

TABLE I—NUMBER OF BACTERIA PER CUBIC CENTIMETER OF SEA WATER AFTER DIFFERENT PERIODS OF STORAGE AT 22° C. IN GLASS BOTTLES AND IN BRASS NANSEN BOTTLES

	Experiment 1		*Experiment 2*		*Experiment 3*		*Experiment 4*	
Period of Storage	*Glass bottle*	*Nansen bottle*	*Glass bottle*	*Nansen bottle*	*Glass bottle*	*Nansen bottle*	*Glass bottle*	*Nansen bottle*
0	94	—	108	—	143	—	294	—
1 hour	86	30	92	25	137	80	253	86
2 hours	72	21	102	18	89	26	222	19
3 hours	90	15	110	10	118	25	266	4
5 hours	52	0	76	3	226	1	207	0
24 hours	446	6	539	0	590	1	890	2

Only when collected from appreciable depths is there a likelihood of the water being in the Nansen bottle for an hour or longer. However, further experiments summarized in Table II indicate that many bacteria are killed or rendered incapable of multiplication in Nansen bottles within a few minutes. The average results of from three to six different experiments with four different Nansen bottles are given. Some of the Nansen bottles had a greater bacteriostatic effect than others, probably due to differences in the metallic surfaces which were exposed to the water samples. It is generally recognized that brightly polished metallic surfaces are more bacteriostatic than those which are coated with oxides or other film-forming substances.

TABLE II—NUMBER OF VIABLE BACTERIA IN SEA WATER AFTER DIFFERENT PERIODS OF STORAGE IN DIFFERENT RECEPTACLES AT 22° C., THE NUMBER BEING EXPRESSED AS THE PER CENT OF THE ORIGINAL NUMBER PRESENT

Time in minutes	*Nansen bottle No. 3*	*Nansen bottle No. 13*	*Nansen bottle No. 18*	*Nansen bottle No. 19*	*Glass bottle control*
0	100	100	100	100	100
5	89	94	85	69	103
10	77	82	74	62	95
30	71	78	56	40	96
60	42	70	51	36	92

GLASS BOTTLES

After trying different sizes and kinds of flasks, test tubes and bottles it was found that citrate of magnesia (CM) bottles with a one-hole rubber stopper substituted for the patented stopper, or ordinary pop or beer bottles are the best for collecting water samples. They are economical, rugged in construction, of sufficient volume and they stand erect on their flat bottoms without the need of special racks. Moreover, unlike the test tubes used by Wilson (1920), Gee (1932) and ZoBell and Feltham (1934) there is less tendency for the stoppers to be pushed in by the hydrostatic pressure. This can be prevented completely by inserting a piece of 8 mm. glass tubing of such a length that its ends rest upon the bottom of the bottle and the lower end of the stopper.

The use of the specially bent capillary inlet tubes as devised by various workers are somewhat difficult to construct and they are easily broken during sterilization, transportation or handling. The use of a piece of pressure rubber tubing, as used by Schach (1938), provides for flexibility and greatly simplifies the construction of the piece of glass that is broken at the time a sample is collected. Combining the most desirable features of the samplers of Schach (1938) and ZoBell and Feltham (1934), we have a device which is simple to construct and positive in action.

By means of a No. 1 one-hole rubber stopper a CM bottle is fitted with a four inch piece of 5 mm. glass tubing bent at right angles one inch from the end. The longer piece of the resulting L goes through the stopper into the bottle and the shorter arm is fitted with a four inch piece of ⅛ inch heavy-wall rubber pressure tubing. This part of the apparatus can be used over and over again almost indefinitely. The piece of projecting rubber tubing is fitted with a four inch length of 4 mm. glass tubing hermetically sealed at the outer end in a flame. The assembled apparatus is sterilized in the autoclave with the stopper resting loosely on the neck of the bottle held in place by the extruding glass tube. As soon as the bottles can be removed from the autoclave, preferably while they are still full of steam, the stoppers are firmly seated exercising aseptic precautions. When cool the bottles will be from 50 to 90 per cent evacuated.

To collect a sample of water the bottle is clamped into the brass carrier illustrated in Figure 37. The rubber tubing is bent around at an angle of 180° and held in this position by the spring clamp T. C. which is operated with the thumb. When lowered into the water to the desired depth the messenger is dropped. The glass tubing

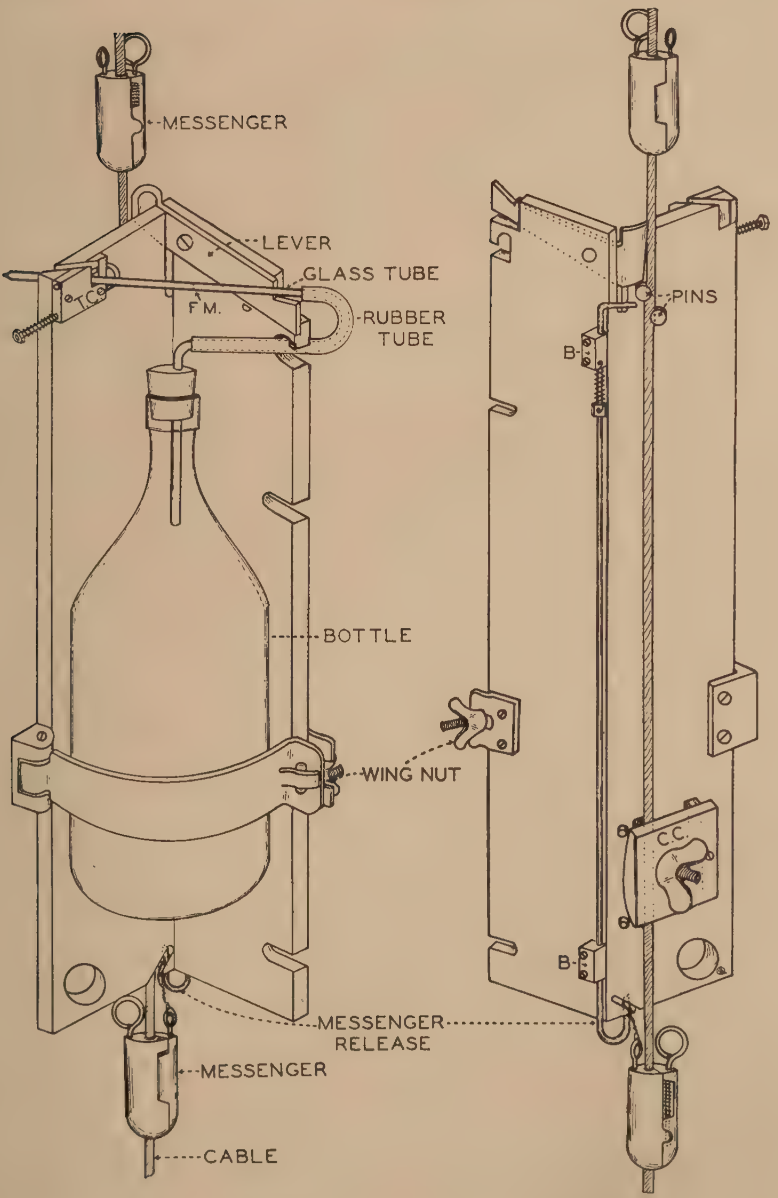

MESSENGER
LEVER
GLASS TUBE
T.C.
F.M.
RUBBER TUBE
BOTTLE
WING NUT
MESSENGER RELEASE
MESSENGER
CABLE
PINS
B
B
C.C.

Figure 37. Front and back view of the J-Z bacteriological sampler.

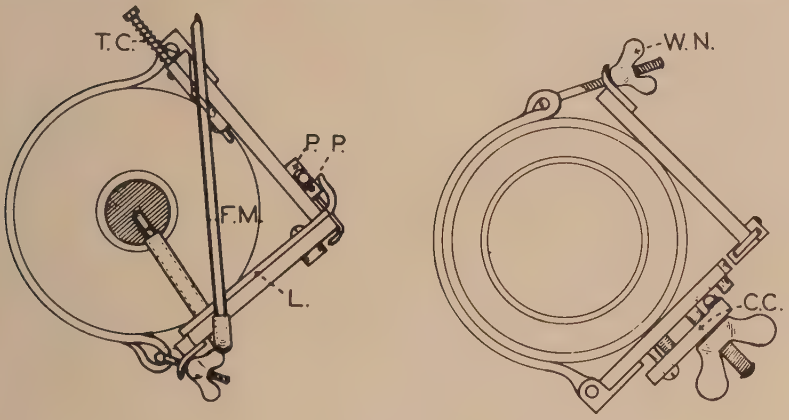
is broken at a file mark midway between the clamp and the end of the lever when the messenger strikes the other end of the lever. Immediately the rubber tubing with the broken piece of the inlet tube flips out to assume a straight position again and a sample of water is aspirated three or four inches away from any part of the apparatus. Even at the instant it is broken the orifice is at least an inch from any part of the apparatus which might carry contaminating organisms, and there is no need for the operator to touch the inlet tube after it is sterilized.

The carrier is constructed of a piece of ¼ inch angle brass 2 × 2 inches wide and 11 inches long. The clamp for holding the bottle in place is made of a six inch length of ⅛ inch strap brass one inch wide bent in a semi-circle. One end is hinged to the carrier frame 4½ inches from the bottom and the other end is fitted with a bolt by which the brass strap can be tightened against bottles of different sizes with a wing-nut. A ⅛ inch notch ½ inch deep to accommodate the rubber tubing is cut over the top of the carrier, the bottom of the notch being 1½ inches from the top of the carrier frame. The notch is made somewhat larger at its inner end to help secure the rubber tube when pushed into the notch. The top corner is cut out as illustrated in Figure 38 to accommodate the inlet tube when the latter is bent into place. On the other side of the carrier a notch 3/16 inches wide and ¾ inches deep is cut at an angle of approximately 45° to accommodate the end of the glass inlet tube. The latter is held in place by the spring clamp made of a piece of brass rod bent U-shaped (T. C. in Figure 38).

The carrier is attached to the sounding wire, cable or rope by means of a wing-nut clamp on the back of the carrier. It is maintained in an upright position by placing the wire in the slot between the two pins P. P. When only one sample is to be collected there are simpler methods for attaching the carrier to the end of a rope, for example, but the sampler as illustrated is designed for rapid attachment to a hydrographic wire or cable.

The ⅛ inch brass rod shown in Figure 38 extending along the outer corner of the carrier is for releasing a messenger which is hooked on the bottom of the carrier. The upper end of the rod is bent over at an angle of 90° so it is engaged by the lever when the lever is hit by the first messenger. This forces the rod to slide down and in so doing the lower U-shaped end slides out of the 3/16 inch oblique notch cut in the bottom of the carrier. This releases the second messenger which then slides down the wire or cable to activate other apparatus attached below. The ⅛ inch brass rod is held in position by the bearings BB. These are constructed from pieces of brass ¼ inches thick and ⅝ inches square. After drilling a ⅛ inch hole along the edge of them they are fastened in place with two ⅛ inch machine screws although they can be soldered to the carrier frame. The brass rod is held in position by means of a spring.

This device with the attached glass bottle has proved to be satisfactory for collecting water samples when used singly or on a line in combination with other apparatus in lakes as well as in the ocean. As many as eight of them fastened seriatum on the same line have made it possible to obtain samples from eight different depths in one cast. The repeated failure to recover test pigmented bacteria purposely applied to all parts of the carrier, the cable and the messenger proves that uncontaminated water samples can be collected under the most rigorous conditions. After a few words of instruction, uninitiated deck-hands and technicians alike can collect uncontaminated water samples with the apparatus suitable for bacteriological analysis.



TOP VIEW

BOTTOM VIEW

Figure 38. Top and bottom view of the J-Z bacteriological sampler with a citrate of magnesia bottle and its connections in place.

In order to get a sample of water near the surface it is necessary to have the bottle partly evacuated. However, at depths exceeding 10 meters the bottle rapidly fills with water even if the bottle is not evacuated, the time required for the bottle to fill decreasing with depth due to the increasing hydrostatic pressure. Once equilibrium has been established, which requires from two to ten minutes after the inlet tube is broken, there is no possibility of water from higher levels entering the bottle as it is pulled toward the surface because the pressure within the bottle is greater than that in the water at higher levels. Actually there is a slight tendency for water or air to be forced out of the bottle as it is raised. Sometimes when bottles fitted with small capillary tubes are hauled rapidly to the surface they appear with a fine jet of water being ejected.

Although the hydrostatic pressure aids in the collection of water samples, it prevents the apparatus from being used successfully at all depths. Some of the CM bottles will be crushed by the hydrostatic pressure at depths between 200 and 300 meters. The trial immersion of over a hundred stoppered CM bottles tied in groups on the submerged sounding line showed that 7 per cent of them were broken at 200 meters, 29 per cent at 300 meters, 81 per cent at 400 meters and all of them were broken at 600 meters. Although most water samples for bacteriological analysis are collected from the principal biotic zone which rarely exceeds 200 meters, in exploring the abyssal depths of the sea, it is desirable to have a bacteriological sampler which will function at depths exceeding 10,000 meters. Bacteriologists have been seeking such an apparatus for several years.

A PRESSURE RESISTANT BOTTLE

None of the so-called "deep sea" bacteriological water sampling bottles has been designed to function at depths exceeding a hundred meters or so, with the possible exception of those filled with a disinfectant (Matthews, 1913, Drew, 1914).

As mentioned above, valves and pistons on metal bottles are not leak-proof as far as bacteria are concerned. Evacuated glass bulbs which are large enough to collect a satisfactory sample are broken by the high hydrostatic pressure encountered at greater depths. The best high pressure bottle we could find without going to the expense of having special ones fabricated was a 125 ml. thick-walled flask with a round bottom supplied by the Corning Glass Company. It was cracked at a depth of 1200 meters.

While unquestionably glass bottles holding 100 ml. or more could be fabricated to tolerate any pressure in the sea, the cost is excessive and, moreover, it is doubtful if evacuated bottles should be used at great depths for collecting water samples for bacteriological analysis. When the capillary inlet tube on such a bottle is broken at a depth of 1000 meters, for example, the bacteria aspirated with the water sample are subjected to an instantaneous pressure change of approximately 100 atmospheres, and correspondingly greater pressure changes at greater depths. The recovery of viable bacteria by Certes (1884), Carey and Waksman (1934) and others from depths near 5000 meters proves that neither the pressure encountered (approximately 500 atmospheres) nor its gradual release, effected by bringing the samples to the surface, killed all of the bacteria but it is indeterminate if some failed to survive this change. The work of Larsen et al. (1918) indicates that while certain bacteria tolerate pressures of 6000 atmospheres (about six times as high as any encountered in the sea), they are injured by the sudden release of pressures of 50 atmospheres or less depending upon the gas tension and other factors.

After experimenting with many types of devices to obviate the pressure factor for collecting samples at great depths, we have perfected the collapsible rubber bottle idea suggested to us by Dr. Austin Phelps of the Hopkins Marine Station. In its simplest form heavy rubber pear-shaped aspirator bulbs holding around 100 ml. are used (Figure 39). A 5 inch length of ⅛ inch heavy rubber pressure tubing is cemented in the 6 mm. opening of the rubber bulb with rubber cement. The rubber tubing is fitted with a 4 inch length of 4 mm. glass tubing with the outer end sealed in a flame, this part of the apparatus being the same as that used with the CM bottles described above.

The rubber bulbs can be sterilized in the autoclave after which the inlet tubes with the sealed ends are fitted aseptically with the bulb collapsed or depressed. At sea they can be sterilized by boiling, or in an emergency they can be sterilized by filling with 70 per cent alcohol or other disinfectant and then rinsed with sterile water after squeezing out the disinfectant, exercising aseptic technique. In practice we prepare and sterilize in convenient receptacles or paper-wrapped packets several hundred of the glass inlet tubes preparatory to embarking on a cruise. The rubber bulbs are sterilized by boiling or in a pressure cooker as needed, the bulbs being fitted with the glass inlet tubes while the former are still quite warm to lessen the likelihood of contamination and to get a better evacuation of the bulbs.

These rubber bulbs function in precisely the same way as the similarly fitted CM bottles. When the capillary inlet tube is broken by the lever activated by the messenger, the rubber bulb aspirates a water sample as it assumes its normal shape. It cannot be broken by the pressure regardless of whether it is collapsed or inflated with air because as it is compressed by the increasing hydrostatic pressure, the pressure will always be nearly the same inside and outside the bulb due to the flexibility of the rubber. Consequently there is very little pressure change as the water sample is aspirated.

The rubber bulbs are secured to the same carrier as is used for the CM bottles by means of an auxiliary collar made of a 1¼ inch length of brass pipe 1⅛ inches in inside diameter. A hole is drilled ⅜ of an inch from the edge of the collar and threaded to take a ¼ inch machine screw 1¼ inches long having a knurled or wing-nut head. Two nuts are placed on the screw as illustrated in Figure 39 to keep the collar and attached rubber bulb in the proper position in the carrier. The collar is slipped over the neck of the sterilized pear-shaped bulb which is ready for use. Then the bulb is placed in position on the carrier and fastened there by slipping the screw projecting from the brass collar into a ¼ inch slot which is cut ¾ inches deep 4 inches from the top of the carrier. It is secured by tightening the machine screw and in so doing the end of the screw presses into the neck of the rubber bulb for about ⅛ inch thereby preventing the bulb from dropping out under any conditions. The collars are made detachable to facilitate handling the water samples collected in the rubber bulbs as well as to facilitate the sterilization of the latter and their assembly.

The trial immersion of the assembled rubber bulbs to depths exceeding 4000 meters without breaking the inlet tube proved that they were leak-proof. When the inlet tube was broken by the messenger-activated mechanism, the bulbs came up filled with water. Although we have not had an opportunity to send them down to the greatest depth in the sea, there seems to be no reason why they will not be just as efficient at 10,000 meters as at 4000 meters.

With the brass collar removed the rubber bulbs stand in an upright position on their flat bottoms. The sample can be transferred to a sterile glass container by squeezing the bulb, or aliquot portions can be removed as needed. The water samples should be stored in the refrigerator until they can be analyzed, although to insure reliable results the water should be analyzed for its bacterial population as soon as possible to minimize the changes which accompany the storage of water samples (ZoBell and Feltham, 1934, ZoBell and Anderson, 1938).

Since the rubber is not entirely inert the samples should not be left in the rubber bulb any longer than is necessary. There are certain bacteria found in the sea which slowly attack rubber as well as the synthetic products, neoprene and isoprene, as manifested by

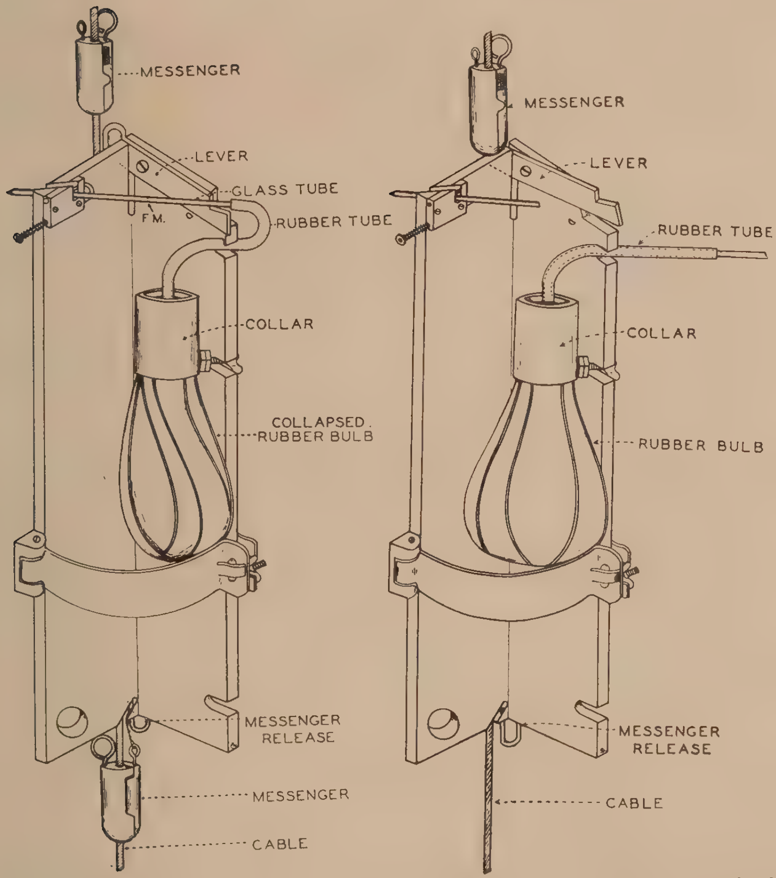

MESSENGER
LEVER
GLASS TUBE
F.M.
RUBBER TUBE
COLLAR
COLLAPSED RUBBER BULB
MESSENGER RELEASE
MESSENGER
CABLE
MESSENGER
LEVER
RUBBER TUBE
COLLAR
RUBBER BULB
MESSENGER RELEASE
CABLE

Figure 39. J-Z bacteriological sampler fitted with a pressure-resistant collapsible rubber bottle before and after collecting a sample of water. TC, thumb clamp, PP, pins for guiding cable; FM, file mark on glass inlet tube; L, lever which breaks tube; WN, wing nut on bottle clamp; CC, cable clamp for securing apparatus to cable.

oxygen consumption and the increasing bacterial population after several days. However, there is no evidence that the rubber is attacked for several days, so this possible source of error can be discounted provided the water samples are not left in the rubber bulbs for more than a few hours. The bacterial population and other properties of water samples of known bacterial content stored in rubber bulbs for 24 hours were not unlike those of water stored in glass receptacles under comparable conditions.

Several hundred water samples for bacteriological analysis have been collected from various depths in the sea proving the apparatus to be quite satisfactory. The sampler is known as the "J-Z" because of the activities of the S. I. O. mechanic, Carl I. Johnson, in perfecting the carrier.

SUMMARY

None of the numerous samplers which have been described in the literature is entirely satisfactory for the collection of water samples for bacteriological analysis.

Containers made of copper, zinc, tin or nickel alloys are not suitable for the collection of samples of sea water for bacteriological analysis due to the inimical oligodynamic action of the metals. Many bacteria are killed and the sea water itself may be rendered bacteriostatic by exposure to the metals.

An apparatus is described which can be used on the standard hydrographic wire or cable for the collection of water samples aseptically from any desired depth in the sea. Multiple units provide for the simultaneous collection of samples from several different depths or the bacteriological sampler, known as the "J-Z", can be used in conjunction with other hydrographic sampling bottles and instruments. Glass bottles can be used to advantage for collecting samples at depths not exceeding 200 meters and collapsible rubber bottles are recommended for greater depths. High hydrostatic pressures do not interfere with the operation of the rubber bottles.

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Contribution No. 151

Twenty Years' Statistical Studies of Marine Plankton Dinoflagellates of Southern California

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Twenty Years' Statistical Studies of Marine Plankton Dinoflagellates of Southern California*

Winfred Emory Allen

Introduction

Adrift in Southern California seas two distinctly different types of microscopic organisms possessing powers of photosynthesis are represented continuously and are able to reach notable abundance with considerable frequency. These are the diatoms and the dinoflagellates. On account of their greater abundance in most of the Scripps Institution collections the diatoms are discussed more extensively in other papers (Allen 1936 and earlier). Discussion in this paper is limited to the dinoflagellates, and it deals mainly with representatives of only a few of the major groups, the exact designations and limitations of the groups depending on what authority is consulted for classification. It is not even possible to find full agreement as to their being plants, although recent botanical books (e. g. Fritsch 1933) give good arguments for considering all of them plants.

For present purposes it is unnecessary to give particular attention to classification beyond saying that the organisms under consideration are microscopic, biflagellated, unicellular plants adrift in the sea, mostly included in seven genera; i. e. *Peridinium, Ceratium, Goniaulax, Prorocentrum, Dinophysis, Noctiluca,* and *Gymnodinium.* The genus *Gymnodinium* is used here as a catchall for the numerous unarmored forms appearing in the collections. A few other genera are represented in negligible numbers in Scripps Institution series of catches.

It is probable that all specimens included in Scripps Institution records are photosynthetic in activity, and therefore eligible to consideration as components of "ocean pasturage." On the other hand, there is evidence to suggest that their nutritive values, or characters, are hidden at times by characters injurious to animals (cf. p. 13) which are developed or exhibited when dinoflagellates appear in dense populations (Allen 1921a, 1921b, 1933, and other papers).

Phytoplankton investigations of 1917 (first year) and 1918 were unsatisfactory for a number of reasons: First, there were no standard stations at which permanent series of continuing and frequent observations could be made in order to establish and improve a reliable basis of understanding of conditions normal to the region. Second, it was impossible to standardize the operation of tow nets or to avoid the numerous widely ranging errors (Allen 1921a, p. 540) due to progressive clogging of the meshes, to irregular movements in

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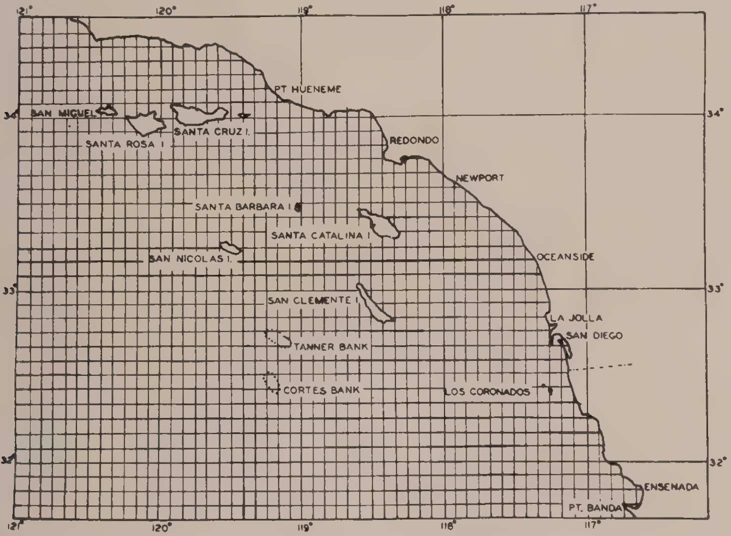
hauling, and to mixing of populations not actually associated in certain spots or levels traversed. Third, it was impossible to know what volume of water yielded any particular catch, much more or much less water being filtered by any particular tow than was filtered by some others of the same distance and duration. Fourth, tow nets demanded great skill in hauling and favorable conditions for handling. Fifth, the cost of equipment and the loss of time involved in using tow nets for extended series of phytoplankton collections was too great.

Therefore, when phytoplankton investigation was advanced to the status of a full time activity of the Scripps Institution in 1919, improvements of methods and procedures received immediate attention and careful study. As a result, the measured water method was adopted as standard (Allen 1921b, 1936). Until 1929 the routine of using this method by the Scripps Institution was as follows: A known volume of water (five to twenty-five liters) was dipped from the sea and filtered through a small conical net of No. 25 bolting silk (80 meshes per centimeter or 200 meshes per inch, linear in new material). Sometimes the water was measured before pouring through the filter, sometimes as it came from the filter. The Kofoid (1911) closing bottle was used for getting samples below the surface in a few series. Later, the smaller and lighter Allen (1927) closing bottle was used for subsurface sampling. For catching the larger, armored dinoflagellates, this filtration method was probably as dependable as any in addition to being easier and faster in routine operation. For smaller forms, it was less satisfactory; the losses of *Prorocentrum* and others through the meshes of the filter creating a notable uncertainty. Still, most of the catches were good enough to show the main tendencies in occurrence and distribution of the dinoflagellates as a group.

Partly for convenience but mainly for better catching of smaller forms a concentration (settling) method of collecting was adopted in 1930 for the Scripps Institution pier in place of the filtration method which had been used through the first decade. One liter of water was placed in a glass cylinder with enough formaldehyde (five to ten milliliters) to kill the organisms for removal after twenty-four hours by successive decanting and pipetting.

Laboratory treatment of catches consisted in the routine of counting the organisms in a measured fraction of a catch, in one milliliter of water in a Sedgwick-Rafter counting cell, under a compound microscope. For thin populations in clean water the fraction was usually one tenth of the Sedgwick-Rafter sample. For dense populations or heavily silted catches it might be as little as one hundredth for particular species in a much diluted sample, representing no more than five thousandths of a liter of untreated water in a few cases. The magnification used for counting was usually about one hundred diameters. From the count records the numbers in the catch were estimated, and from these estimates calculations were made of the numbers per liter in the water sampled. In the later years separate calculations were made for those specimens in good condition (alive or viable when caught) and for those in bad condition. The series of records thus obtained were used for finding relative densities of dinoflagellate populations in periods of days, weeks, lunar months, seasons, and years. They were used also for comparing occurrences of entire dinoflagellate populations or of selected species under natural conditions in one or several localities.

The largest number of catches (about 6,500) was obtained from the water at the seaward end of the pier of the Scripps Institution of Oceanography, on La Jolla Bay, a little north of San Diego Bay on the Gulf of Santa Catalina (see map Fig. 1.) Almost as many were taken from a similar position inshore at Pt. Hueneme, more than one hundred miles northwestward. About 2,000 catches were made at other inshore stations between these, and some thousands were made at offshore positions on different trips by boat. In addition, a number of series of collections from the surface level were made in localities more or less distant from California. Altogether, more than twenty-five thousand catches have been examined at the time of this writing in 1940.


121°
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118°
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PT HUENEME
34°
SAN MIGUEL I
SANTA CRUZ I.
SANTA ROSA I
REDONDO
NEWPORT
SANTA BARBARA I.
SANTA CATALINA I
SAN NICOLAS I.
OCEANSIDE
33°
SAN CLEMENTE I
LA JOLLA
SAN DIEGO
TANNER BANK
CORTES BANK
LOS CORONADOS
32°
ENSENADA
PT. BANDA

Fig. 1. Map of coastal waters of Southern California to show location of standard stations La Jolla and Pt. Hueneme in region of greatest activity in oceanographic research of Scripps Institution.

Ocean Habitats

A considerable success in understanding and controlling the life of land plants has been attained without very prominent attention to the phenomena of stratification in the various habitats. Such neglect of important conditions in space relationships may be due in part to the knowledge of investigators that many kinds of conditions in levels both above and below the soil surface may differ or change suddenly and extremely, and that in some cases these changes occur often.

But the student of plant life in the sea who seeks to understand the conditions of its existence cannot escape a continuing emphasis upon the importance of distance below the surface, whether stratification be recognizable or not. There, he finds that vertical zonation is rarely less important than horizontal zonation, and that it is more important in certain particular investigations. At first, he may feel much relieved by the thought that the pelagic plants are all continuously and completely resident in the one medium, sea water, and that they are so small that their entire bodies can be engulfed in any stratum of observable thickness. He may feel still more relieved when he finds that the sea differs from the land in the relatively high uniformity of its chemical composition, a uniformity so great that the ordinary differences are expressed in thousandths or other small fractions of units. But, he may be greatly disturbed, or confused, when he realizes that these microscopic marine plants may be readily transported from stratum to stratum, or that they may be carried into a turbulent spot in which general mixing of zonal residents, components and inclusions occurs. In fact, if he be requested to characterize an ocean habitat he may be unable to decide whether the locality showing an observed population, or the mass of water carrying it, or the series of localities concerned in its production shall be designated.

On the land it is possible to select individual plants, or groups of plants, for study in relation to a specific place of residence. In study of the drifting populations of the sea it is necessary to select a place of observation and to use whatever plants are found in it from time to time. If a locality be selected for study on land, one expects to find its population fairly stable over a considerable period of time. In the sea, a dense population of a particular kind may appear in an observed locality for a few hours or days, not to be strongly represented again for years. A plant or a population may appear at a level at which it is not usually found, or it may be found most often at a certain level in one locality and at different level in another. Ordinarily, the constant movements of the plants in one direction or another add enormously to the difficulty of conducting researches and of understanding the results of researches.

When discussing the habitat relationships of phytoplankton, the fact that populations are themselves significant features of their own habitats should not be neglected. Not only are they continuously modifying their immediate surroundings but they are also modifying themselves. In the ocean, both types of changes are likely to occur with remarkable speed and abruptness, e. g. when an increasing phytoplankton population modifies its activities as nutrients decrease, while changing the forms of these nutrients in such ways as to accelerate or retard solution, decomposition, or formation anew of numerous sea water inclusions.

In consideration of the foregoing, and of a number of other points which might be mentioned, it seems that ocean habitats in the sense of places of residence of particular phytoplankton populations are as varying and as varied as the populations which they support. Not only does one locality differ from some other at any given time, but it also differs within itself from time to time. However, these differences in respect to space, time, and population history tend to show recognizable groupings according to geographic relationships. Most clearly exhibited is the fact that shallow depths like those of La Jolla Bay entail conditions of temperature, complex water movements in all directions, and inclusions of materials from land not to be found at any time in mid ocean. Still, it may be difficult to determine the relationships of phytoplankton populations to one region as distinguished from the other. Perhaps one may say with considerable assurance that the high seas directly off shore from La Jolla Bay have no influence upon it, or it upon them, the general circulation of the Gulf of Santa Catalina being too strongly effective upon the water masses between them. On the other hand, it is impossible to believe that production of phytoplankton in La Jolla Bay would be the same as now if the deep ocean were not out there.

When the measured water method of collecting was first adopted at the Scripps Institution of Oceanography in 1919, so little was known about the distribution of phytoplankton in relation to locality differences of habitat that no effort was made to identify habitat peculiarities at the Institution pier. The sufficient reason for collecting there was proximity to the home laboratory with its most favorable opportunities for convenience in operation and continuity in observation. As soon as daily collections showed the probability that samples of phytoplankton obtained at this inshore station were fairly representative of the region, plans were made to begin daily series of collections at one or more stations in other localities in order to compare the information obtained from them with that being accumulated at the home station. Consequently, in February 1920, daily (except Sunday) collections were begun at Pt. Hueneme, near Oxnard, California. The immediate reasons for selecting this station were: that it was more than one hundred miles distant from the home station; that it was already being used by the Scripps Institution for hydrographic observations; that a dependable collector resided there; and that its location north of the Gulf of Santa Catalina suggested the presence of recognizable habitat differences.

Even in 1940, positive knowledge covering the details of significant habitat differences at these two places is lacking. The most that can be said is that certain gross features characterizing them seem to be observable. The existence of lower temperatures of sea water month by month (Fig. 2) at Pt. Hueneme is clear. So, also, is the slightly longer duration of winter influences. Greater turbulence at this station at the eastern end of Santa Barbara Channel is to be expected, and there is evidence that it exists. Also the relative proximity to fairly large islands and to a more considerable land drainage suggests the probability that significant differences do exist there. But, aside from these imperfectly defined features, there is little known about monthly, seasonal, and annual, or cyclical differences in the ocean in the two localities.

Concerning the home station, it may be noted that the Scripps Institution pier, one thousand feet in length, is located on the eastern shore of La Jolla Bay, near the northern end of a mile-long, gently sloping beach, and at the southern end of a four mile series of cliffs, based on moderately hard sedimentary rocks and faced with varying aspects of conglomerates and of silty shales of differing degrees of hardness. The nearest stream of appreciable size enters the ocean at the northern end of this series of cliffs, except in the dry

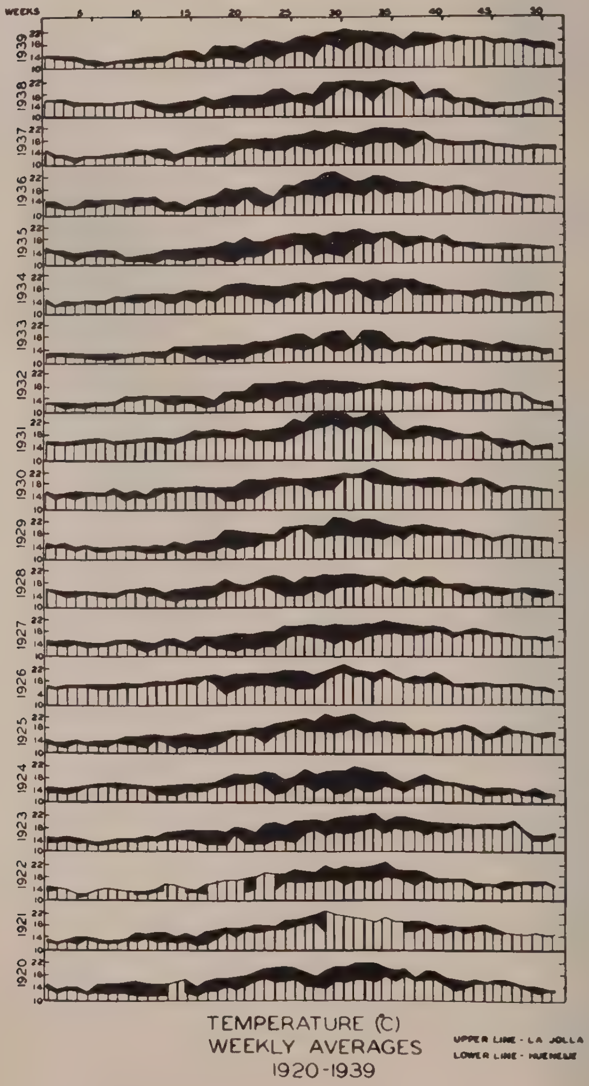

Fig. 2. Graphic representation of yearly temperature progressions; shaded between lines to stress station differences. Upper margin La Jolla. Lower margin Pt. Hueneme.

season. The beach occupies about two-thirds of the base of a triangle with its apex about a mile seaward from the end of the pier, the southwestern side consisting of a submerged canyon deepening to a thousand feet or more at the apex where it is joined by a similar canyon of nearly westerly trend which extends from shore about a half mile north of the pier. On the triangle the slope increases very moderately to seaward until much steeper contours occur at about two thousand feet from shore, the depth at the end of the pier being less than twenty-five feet at ordinary high tides. The pier extends a little north of west. In this position it is exposed directly to the open ocean, the nearest obstruction off shore being San Clemente Island at a distance of more than sixty miles.

As recently as 1919 the beach terminated in a rocky shore a few yards north of the pier. In those days it was sometimes denuded of sand throughout half its length in winter seasons when the underlying rock strata became bare where not covered with enormous deposits of "cobble stones" four inches or more in diameter. At other times the sand deposits of the beach might be increased by depths of two or three feet temporarily. In more recent years, these seasonal changes have been less evident and the beach has been extended northward over the rocky foreshore until it has become difficult to find good tide-pool collecting grounds, except at lowest tides, within a short distance of the pier. Such changes are probably incidental to the cutting back of the shore cliffs many yards by surf erosion (Shepard and LaFond 1940). Whatever the causes of changes in the beach levels and the like, these seasonal changes indicate that there must be marked disturbance in the waters of La Jolla Bay at times. The little evidence available concerning water movements outside of the limits of the small bay suggests that no prominent turbulence exists there, although the bottom contours may cause a certain amount of mixing of currents.

In general, therefore, it appears that oceanic waters may come into La Jolla Bay without being greatly influenced by conditions peculiar to the immediately surrounding territory. If this be true, one finds it impossible to suppose that the phytoplankton collected at the Scripps Institution pier is necessarily a product of La Jolla Bay or a resultant of the environmental conditions found there. In a period of long continued calm weather, perhaps the Bay does have a high degree of influence. In a whole year of very mild weather the local influence may be continuously notable, but in most years there must be long periods in which the local influence is relatively negligible in determining the condition of the populations there. Doubtless, many of the striking peculiarities of occurrence and abundance in different seasons and years are due to differences in degrees of prominence of local influences at the different periods. The only reliable conclusion available seems to be that La Jolla Bay may or may not exert notable influence upon the populations sampled within its limits, depending on the extent to which water movements, or lack of movements, permit its conditions to operate before the population shifts to another locality or disappears.

Why, then, do the phytoplankton populations of the Bay differ from those at any particular locality of similar extent off shore? The evidence to support a dependable or comprehensive answer to this question does not exist. We must be content with certain inferences drawn from our limited knowledge of occurrences of populations and of selected features of the habitats so far sampled. Populations observed show that surface samples at the Scripps Institution pier and at considerable distances offshore may be closely similar, although recognizable differences are more likely to be found. Inasmuch as the shallow depth of water at the pier is sufficient alone to constitute a fundamental difference from any off shore habitat, it is surely true that the presence of similar populations in places more or less distant from each other is not a dependable indication that habitat conditions are also similar to a like degree. Three or more combinations or sequences of circumstances may be responsible primarily for this kind of irregularity. First certain environmental features (e. g. abundance of phosphate) may be so prominent over a wide territory at some particular time that they cause production of particular populations in spite of local dissimilarities of other features recognizable but not detrimental within the limits of observation (e. g. high temperatures or unusual cloudiness). Second, the two populations inshore and offshore may have been drifted into their separate localities from a locality of common origin so recently that they appear to retain the earlier likenesses in recognizable form although already acquiring important differences. Third, a population developed in an area more or less off shore may be expanded into such an area as La Jolla Bay, adapting itself to environmental features of secondary, or tertiary, or more remote influences as the expansion progresses.

Importance of Plankton Dinoflagellates

Bigelow (1926), Bigelow and Leslie (1930), Kofoid and Swezy (1921), Lebour (1925), Fritsch (1935), West (1916), and other authorities ascribe great importance to the pelagic dinoflagellates, rating them second only to the plankton diatoms as contributors to the basic food supply in the open sea. However, Fritsch and some others are disposed to question the validity of an assumption that phytosynthetic activities of all planktonic vegetation are superior to those of all sedentary marine vegetation in providing food for animals inhabiting sea water. Still, in the absence of reliable data to prove superiority in food production for either pelagic or sedentary vegetation, it seems reasonable to give plankton dinoflagellates a high general rating, especially when it is recalled that they contribute largely to sustenance of sedentary animals as well as to those of free living habit. In addition, their influence on oxygenation and other chemical changes in sea water surely qualifies them for a prominent place when considering influences of organisms in the sea. Even though they be rated below pelagic diatoms in volume of constructive metabolism, as seems reasonable, they require attention because of the frequency of their occurrence in high abundance in many localities, and because of the possibility that peculiarities of their occurrence may serve to indicate the presence and distribution of chemical, physical, or biological conditions of localized water masses which might be overlooked otherwise.

Evidence of Productivity

Most of the literature which gives high rating to dinoflagellates as producers in the food chain, or food cycles, of the sea is barren of proof to support the assumption. As a matter of fact, direct proof of production of any designated quantity of nutritive material, or of its consumption or availability for consumption by animals is not obtainable from any large marine area over any considerable period of time. The most that can be done is to assemble evidence suggesting reasonable probabilities within closely limited boundaries and fair probabilities within more remote boundaries. It is believed that the Scripps Institution series of daily records of observations for two inshore stations over a period of twenty years afford the best evidence concerning this point now existing anywhere in the world. Voluminous supplementary records from other Institution series add weight to this evidence.

Statistical studies of dinoflagellates in Southern California were begun on material obtained on boat cruises in 1917 at the same time that similar studies on plankton diatoms were begun (Allen 1921a). Although the methods of collecting by vertical and horizontal hauls of tow nets in 1917 and 1918 were so different from those used later that close comparison of numerical records is impossible, certain gross features of the records of that material collected by boat are still important. In particular, the occurrences of "red water" were remarkable; first, because they were more prominent than others observed by Scripps Institution investigators since that time, except for single occurrences in each of the years 1924, 1933, 1938 and 1939 (Allen 1928, 1933, 1938 and Institution records). Second because in September 1917 *Goniaulax polyedra* Stein made its last recorded appearance until 1938 as a cause of "red water" in the region covered by Scripps Institution investigations. However, these observations may be more interesting than significant because the "red water" of 1917 was found near San Pedro and Santa Barbara in localities rarely visited by Scripps Institution investigators in succeeding years. Still, the indication that *Goniaulax* waned in prominence after that year is not without importance, especially when it is noted that the "red water" of June 4, 1917, near La Jolla, was due mainly to *Prorocentrum micans* Ehr., the dinoflagellates most prominent numerically in the San Diego region up to March 1940.

Failure to find more than the four occurrences (1924, 1933, 1938 and 1939) of "red water" in the Gulf of Santa Catalina since 1917 has not been due to lack of interest in the phenomenon. Two reasons for interest are mentioned in the report on observations of 1917 (Allen 1921a, p. 544), "These two typical cases show not only that plankton swarms occur both inshore and offshore, but that they are to a very large extent exclusive against other organisms in their particular area, many of which, in fact, are killed." Another reason is that such strongly localized occurrences of concentrated plankton populations may indicate incident or related peculiarities of surrounding sea water worthy of special attention.

For support of the assumption, or assertion, that dinoflagellates rank very high as producers of ocean pasturage, most writers rely on reports of vast assemblages of these organisms seen at certain times and places although the observations leading to the reports may be transitory. The fact that organisms may appear in such abundance as to constitute "soupy water" or "red water" as viewed from the surface of the sea is considered good evidence of productivity in general although the reported condition of the water may have been confined to a small locality, to a shallow surface layer, or to a few hours or days in time.

However, it is natural to reach first conclusions about productivity in nature from such gross observations, and the reputations for production or non-production of plants of many land areas have been established in just this way. It is only by subsequent studies of good continuity and extent in time and space that reasonable approximations to true ratings (larger or smaller than the originals) are reached. "Red water" (which always indicates high abundance of organisms) has been reported several times (Torrey, 1902, Kofoid, 1911, Allen, 1921, 1933, 1938) in the Gulf of Santa Catalina, and it has been seen at other times though not officially reported. Presumably, therefore, this region may be supposed to have contributed some support to the idea of high rank in productivity for dinoflagellates. On that account, it is necessary to inquire what relationship observed outbreaks of "red water" have had to total production. In the twenty years of daily observations at La Jolla only four conspicuous examples of "red water" (in 1924, 1933, 1938, 1939) appeared. At another time a small area of "yellow water" was noticed in La Jolla Bay (Allen 1935), and on a few occasions streaks of reddish color appeared in the surf. Still, it is hardly permissible to say that "red water" abundance appeared in more than four years of twenty. Including the outbreaks reported by Torrey in 1902, by Kofoid in 1911, and by Allen in 1921, 1933, 1938, only six occurrences of such abundance are authentically recorded for Southern California in a period of more than thirty years. Nightingale (1937, p. 8) has listed eight occurrences of "red water" from California and Washington coasts since 1878. Obviously the sight of "red water" is important for its impressiveness rather than because of the reliability of its indication of general productiveness of dinoflagellates.

Less frequently mentioned than "red water" as an indication of high abundance is "phosphorescence" (luminescence). At the Scripps Institution of Oceanography remarks have been heard often to the effect that dinoflagellates must be highly abundant because luminescence has been conspicuous in the surf or in the wake of fishes swimming near the pier. Luminescence is a much less reliable indication of high abundance than "red water" because of the fact that a little of it makes a great impression in darkness. Even when dinoflagellates and other luminescent organisms are present in relatively small numbers they give a startling display of light in a collecting bottle when formaldehyde is added to a fresh catch in darkness. Surely, we may conclude that luminescence is even less dependable than "red water" as an indication of productivity, local, regional, or general in space, or periodical in time.

Many years ago, students of plant occurrence and distribution on land learned the lesson that gross inspection (the transitory kind in particular) gave no reliable information as to the productivity of plant populations in a designated locality. Even lumbermen dealing with large trees in forests apparently uniform resorted to detailed examination before making estimates upon which to base their plans of operation. If a plant census is necessary on land where visibility is good, it is more distinctly necessary in the sea where visibility is far inferior. Therefore, admitting that "red water" and other gross phenomena are insufficient as indications, it becomes necessary to base estimates of productivity on census taking fundamentally similar to that used for land plants.

One accustomed to work on land might suppose that a census taken at the surface of the sea would yield an acceptable basis of estimate of productivity for the sea, just as it does on land. However, a liter of water scooped from the surface even in "red water" might show so few organisms as to make him think that the larger abundance must be present a little below the surface. If furnished with proper equipment, he might find that abundance was greater at one meter depth than at the surface, but that it was still greater at depths of five or ten meters. That is to say, he would be forced to realize that no estimate of productivity can be complete unless it be based on census enumerations at all levels in which the organisms (at least the viable organisms) are found. The surface condition might be fairly representative, but there can be no escape from the strong probability that it might be poorly representative, or the possibility that it might be misrepresentative. Furthermore, the streakiness observed in "red water" at the surface indicates strongly that no one sample is closely representative of numbers present, or of density of population, at any selected level.

In the "red water" appearing at the Scripps Institution pier in 1924 (Allen 1928) catches taken at five meters depth were slightly larger for the second week than the regular surface catches. On the other hand, most catches taken at levels below the surface at off shore stations showed larger numbers of dinoflagellates at the surface than at other levels, the numbers usually decreasing at successive levels until few were found at one hundred meters or more. Of course the aggregate of numbers at all lower levels might be greater than the number at the surface, thus showing the surface level as not being truly representative of total numbers in the area or of conditions at other levels.

But, although the results of surface census taking are not completely dependable in estimating productivity of micro-organisms at any particular station or in any particular locality, they are still far more dependable than the results of gross inspection. This is true, not only because gross inspection is so narrowly limited in depth but because populations of large size may be present in numbers too small to cause observed discoloration. Furthermore, relatively thin populations producing over a long period might yield a higher aggregate than a dense population resident for a short period only.

Prior to the accumulation of daily catches recorded in numbers per liter through several years, it had been assumed (e. g. Kofoid and Swezy, 1921) that dinoflagellates were regularly and frequently abundant in the Gulf of Santa Catalina. This assumption, founded mainly on numbers obtained by hauling tow nets through considerable distances (two hundred meters or more) was found to be erroneous so far as armored dinoflagellates are concerned. Catches taken by boat off shore, as well as those taken daily at the pier, rarely showed numbers greater than thousands per liter at any time of year. Indeed, numbers below a thousand per liter were taken more often than numbers above one hundred thousand, And, in the first ten years the totals of all catches for a single year reached a number of one million cells per liter only twice at La Jolla and four times at Pt. Hueneme. To this implication that numbers of thousands per liter do not represent good production, an objection may be offered that pelagic, armored dinoflagellates are so much larger than diatom cells that small numbers may represent nutritive material equivalent to diatom populations showing numbers large enough to suggest

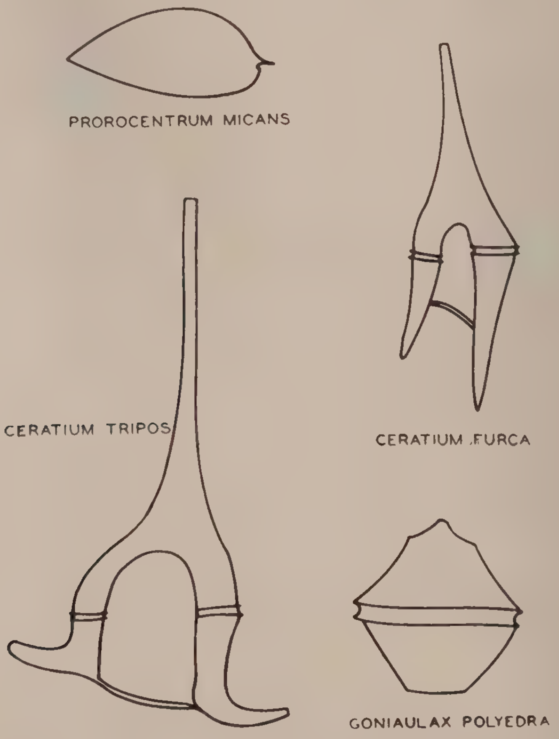

Fig. 3. Free hand sketches of four leading species from measurements of specimens in Scripps Institution collections.

good production. Adequate data for comparison of nutritive values of individual cells of the two kinds of organisms in Nature do not exist. However, this deficiency is not so very important when considering Southern California material because *Prorocentrum micans* (Fig. 3) and other small dinoflagellates contribute most largely to total numbers of the group although the larger forms *Ceratium tripos* (Fig. 3) and *Ceratium furca* (Fig. 3) reach fairly high numbers occasionally and other species rarely. With all due allowance for larger sizes of armored dinoflagellates it seems fair to say that existing evidence does not indicate that their productivity is high in Southern California waters, although their larger size may suggest periods of influence relatively long. On the other hand, it is just as clear that their numbers have not been so low as to be entirely negligible throughout any year of twenty years.

Yearly Differences in Abundance

In dealing with large populations of creatures which are non-visible, both because of minute dimensions and because of physical limitations of the medium in which they are immersed, most observations and conclusions are necessarily more suggestive than positive in character. On the other hand, a good or high frequency of observations carried in regular series over a long period of time tends to offset this deficiency and to give much of the evidence thus accumulated a dependability fully as good as that relating to many populations easily visible. This is true particularly of phenomena such as those of differences in abundance from year to year, or between any two years.

Even a superficial inspection of the graph (Fig. 4) representing week totals per liter for the twenty years reveals that the distribution of numbers of dinoflagellates is different in successive years at both of the two stations observed. As a matter of fact, the magnitude of these differences would be vastly more distinct if space could be used to show the relative sizes of daily catches. Probably it would not be possible to assemble series of records concerning any population of organisms easily visible in Nature which would be more dependable than these as bases of comparison of year differences in gross features of occurrence. In fact, it is doubtful if any visible population in Nature is represented with observations of a frequency sufficient to make it equal to these records in reliability. Therefore, it may be assumed that these records not only suggest but support a fundamental fact i. e. that non-visible populations in the sea are changing in numbers throughout the year and from year to year. This fact is fundamental because it proves that adjustments and re-adjustments of populations are occurring constantly and perennially in Nature and because a correct understanding of marine biology can only be reached through an understanding of the causes and accompaniments of these shifting relationships.

But, although the duration, extent, and seasonal position of periods of abundance is always changing throughout the lapse of a year or of a series of years, there is a general pattern of change to be found in all years (Fig. 5). Furthermore, this general pattern of change is closely similar in at least one

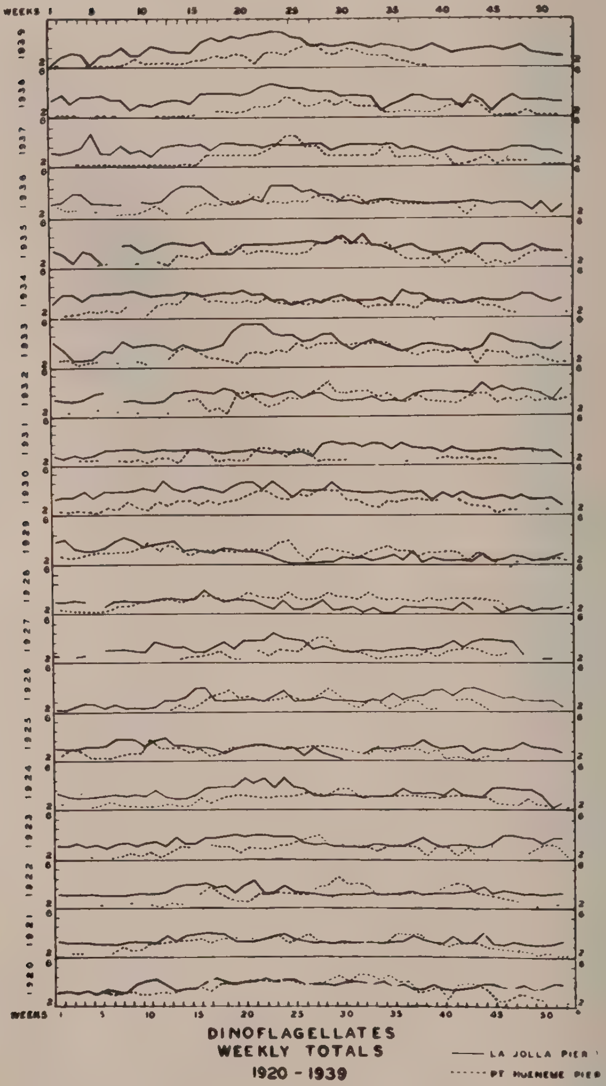

Fig. 4. Graphic representation of weekly successions of fluctuations in abundance of total armored dinoflagellates year by year. Solid line La Jolla. Broken line Pt Hueneme.

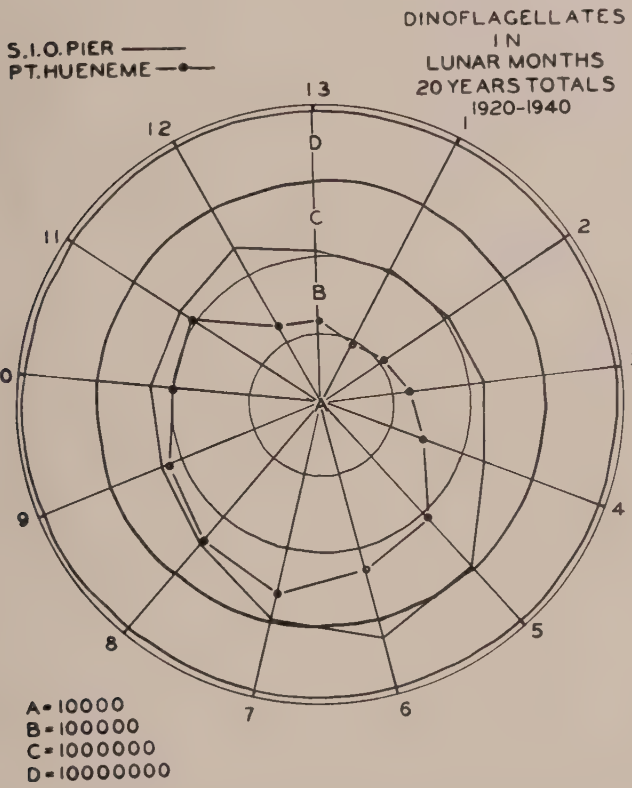

Fig. 5. Twenty year totals for each four week period of annual thirteen; to show trend toward higher abundance in summer in year pattern for abundance of armored dinoflagellates.

gross feature at both of the two standard collecting stations. This particular gross feature is the fact that the six months period halved by the summer solstice is more productive of dinoflagellates (usually much more productive) than the six months period halved by the winter solstice. At Pt. Hueneme, this condition approaches constancy in its annual repetition, but at La Jolla there are enough exceptions to render doubtful the tempting conclusion that productivity waxes and wanes regularly as the supplies of radiant energy wax and wane from the beginning toward the close of each calendar year. Prominent among these exceptions at La Jolla were four-week periods in November-December of 1923, 1924, 1933 and in October-November of 1932 which showed abundances similar to those in median parts of most years. The same is true of two-week periods at La Jolla in January of 1927 and 1936 and in February of 1930 and 1934 (Fig. 4). Still, these exceptions do not prove that the waxing and waning of solar influences is not the most important condition in fixing the annually recurrent pattern of change. Rather, they serve to strengthen the idea that annual and seasonal patterns of change are determined by influences of so great magnitude that they operate demonstrably in localities differing not only in geographic position, but also in numerous conditions affecting production. Local conditions in La Jolla Bay may cause modifications of details of the general annual pattern, but they do not obliterate it. The slightly more erratic occurrences of individual periods of abundance ("pulses") in La Jolla Bay also support this view because of their evidence of temporary responses to localized intensity of more or less closely restricted influences, or particular combinations of influences.

Although the patterns of annual change at the two stations show a discernible likeness in producing dinoflagellates most heavily from April to August, inclusive, there is a fairly regular discernible difference which is almost as interesting, i. e. the earlier exhibitions of annual increase of abundance in La Jolla Bay (cf. Fig. 4). This tendency to earlier increases in abundance of phytoplankton at La Jolla has been mentioned previously in a partial report on plankton diatoms for the first ten years (Allen 1936). The differences between the two stations in respect to dinoflagellates were not so distinct as in respect to diatoms, but they were observable.

Stated in general terms, the foregoing evidence appears to warrant the conclusion that the annual pattern of change is determined by influences primarily solar in origin while the outstanding departures from this pattern are determined by influences ordinarily (or at least immediately) terrestrial in origin. Even the hypothesis of biological cycles characterized by vernal increases and autumnal declines in populations is consonant with this conclusion because of the fact that cycles of this type must have been established originally under solar influences and afterwards maintained by them. Among the terrestrial influences responsible for departures from the annual pattern, and for differences between the two stations such as those noted, topography of sea bottoms and forms of shore lines must be rated highly, especially when considered as influencing characters of currents and turbulences in connection with the fundamental feature of rotation of the earth. Climatic changes and weather conditions, especially precipitation and run off, should not be neglected when considering erratic occurrences of numbers in populations as related to either time or space. And, of course, biological conditions are always basically important in some way. So far as the organisms under special observation are concerned, the season may be favorable, the delivery of solar energy may be just right, the movements of the water masses correct, the food content of the water appropriate and high, and every other observed condition encouraging, and yet there may be failure to produce abundance for the simple reason that propagative ("seed") organisms are absent. Even if they be present, they may be too few, or too feeble, or too sluggish to produce abundantly at the favorable period. Contrariwise, abundance may be missed in the presence of a viable population because some one or more of the solar, or of the physical terrestrial conditions are deficient or unfavorable. Also predatory organisms may decimate a good seeding population before it can develop notable abundance. That is to say, there are plenty of reasons why departures from the annual pattern of abundance at any station may occur, and it is probable that in no two instances are the reasons for the departures precisely the same in all details. However, the fact that certain departures (e. g. the totally low productive years 1926 and 1931) occur similarly at two stations over one hundred miles apart indicates that certain combinations of terrestrial influences may be identified eventually if not immediately.

In addition to likenesses and differences of single years at one station, or at the two stations, there was an interesting grouping of years in the twenty year period. For the first ten years, La Jolla appears to have (Fig. 6) a slightly greater productiveness in the first five than in the second five, the first five also showing greater differences between successive years. The third five shows a return to higher productiveness (although including the very low year of 1931) and there is a strong rise to high productiveness at the end of the last five after a moderate drop. If this showing of alternating five-year periods of

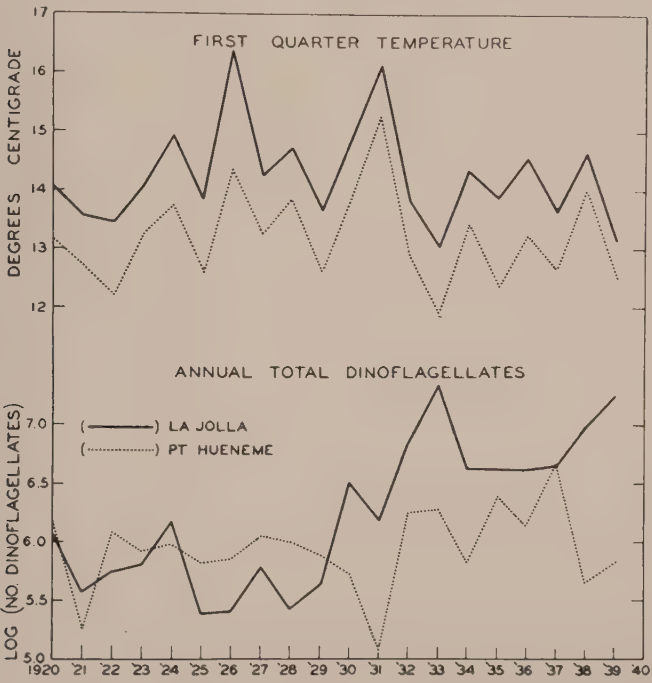

Fig. 6. Graphic representation of possible five and ten year periodicities in production of total armored dinoflagellates, including possible temperature correlations.

greater and lesser abundances indicates genuine cycles, their existence is likely to be related to five-year weather cycles of some kind. As a matter of fact, the change in method of collecting at La Jolla at the end of the first ten years suggests a reason for questioning the genuineness of the appearance of five-year cycles, the smaller organisms having so much more prominence after 1929. However, the subtraction of the records (for the Scripps Institution) of the small forms included under the catchall designation "*Gymnodinium* spp." (nannoplankton) does not entirely obliterate the indication of the five-year cycles and it may be that a trend to such periodicity actually existed. But, perhaps the evidence for a ten-year (or longer) period is a little stronger, especially if we consider the two stations together. To offset any suspicion that larger numbers in the records of the second ten years at La Jolla were due to change of collecting method, we find the showing of Pt. Hueneme distinctly greater for the second decade although no change had been made from the original "filtration" method of collecting. As was true of the five-year periods, subtraction of the "*Gymnodinium*" catchall numbers (nannoplankton) still leaves a distinct showing of higher abundance at La Jolla for the second ten, except for 1931 and 1935. Therefore it seems reasonable to conclude that there are tendencies to cycles of productivity of dinoflagellates in periods of five or ten years, or more (the ten years from 1920 to 1929, inclusive, possibly closing a twenty or fifty-year cycle and the following ten years marking the beginning of another). The full significance of these tendencies is not clear at present, although some relationship to climatic cycles seems highly probable.

In this connection it should be noted that a number of modifications of the annual pattern of distribution of ocean temperatures together with shifts in its sequences discernible in one year as compared with another seem to have recognizable relationships to occurrences of annual differences in the pattern of dinoflagellate production. These relationships are more easily distinguishable in the records for La Jolla pier but most, if not all, are traceable at Pt. Hueneme.

At La Jolla the fundamental year pattern for temperatures appears very simple upon first glance at a graph showing weekly averages for the twenty years, i. e. there is a gradual rise to a peak a few weeks after midyear (Fig. 2) followed by a sharper decline to the end of the year. Closer inspection shows that the condition is not quite so simple as that. In no year of the twenty was the average pattern followed exactly. For example, in 1920 there were two peaks separated by a distinct depression, the maximum finally appearing a little later than might be expected from the idea of the pattern. It is evident also that different years showed marked differences in the ascending and descending slopes. But, regardless of such differences in temperatures between years the pattern of aggregate production of dinoflagellates (Figs. 4 and 5) shows a distinct rise to a peak ahead of the week of highest temperatures. In only a few years do the modifications of this pattern involve notable abundances after peak temperatures have been reached.

It is generally understood that in the temperate zones most of the photosynthetic activity of most land plants occurs after February and before August, a period corresponding closely with that in which dinoflagellates show greatest constructive activity. For that reason, temperatures and accompanying conditions of the first three months of a year are likely to exert influences upon the growth of vegetation which might be traceable, even in Nature. At any rate, it seemed possible that a correlation might be found between average temperatures for the first quarter of a year and the total dinoflagellate production for that year. Herewith (Fig. 6) a graphical presentation is made to show that such a correlation is observable in respect to more than one feature, not only at La Jolla but at both stations.

First, concerning low production in individual years. High temperatures early in 1926 and in 1931 preceded a season of poor production. 1925 seems to present an anomaly, its year aggregate being similar to that of 1926 although the average temperatures for the first three months were relatively low. Possibly unusually low temperatures in December of 1924 give a clue to this problem if we knew how to follow it. In a correlation of this kind, it is not to be expected that temperature alone is operative. Rather, it is the physical and chemical complex represented by temperature which is decisive, too intricate for us to follow. In many instances where temperature is credited with the deciding influence it is little more than an indicator of a deciding influence which is confusingly indirect or complex or both.

Second, concerning high production in individual years. The correlation seems to be fairly good at La Jolla, not so good at Pt. Hueneme, although not contradicted by records for the latter. At La Jolla production was excessive in 1932 and 1933 after low temperatures. In 1938 it was excessive after a temperature average approaching the median for twenty years. In 1939 it was excessive after an average markedly lower. However, in spite of the discrepancies the evidence for a correlation is at least good enough to demand attention.

Taken by decades, the evidence for correlation appears to a little better advantage, temperatures at both stations running somewhat warmer over the relatively unproductive first ten years than over the highly productive second ten.

Supplementary Inshore Stations

At this point it seems appropriate to remark that inshore observations were not confined to the two stations (La Jolla and Pt. Hueneme). As a matter of fact, supplementary series of daily catches were run for five years or more at four other stations, i. e. Oceanside (Fig. 1, twenty miles north of La Jolla), Balboa (Newport Bay Fig. 1, seventy miles north of La Jolla), Farallone Islands Light House (off San Francisco Bay), and Scotch Cap Light House (Aleutian Islands). The Oceanside series was terminated in five years because the annual pattern of production resembled that of La Jolla so closely that the extra effort seemed unnecessary pending the development of better general understanding of phytoplankton distribution. The Balboa series was never dependable because of local difficulties of operation which led to abandonment after five years. At Farallone Light no large catch was ever obtained and most catches were too small to be significant, a condition which led to discontinuance after five years. Difficulties of communication caused some breaks of continuity at Scotch Cap Light but the series as a whole was good for about seven years and it was dropped partly because of increasing pressure of phytoplankton routine and partly because it was felt that other institutions should be able to handle it better because of being nearer to that region. The annual pattern of phytoplankton occurrence had a considerable resemblance to that of Southern California except that the numbers of dinoflagellates were negligible throughout the period of observation (Cupp 1937). So far as the relationships to the present discussion are concerned, the main value of information from these supplementary series lies in the showing that the two standard stations are fairly representative of general conditions, trends, and fluctuations of phytoplankton occurrence and production inshore. However, the point must not be neglected that they show also distinct differences in localities in respect to these phenomena.

Short series of collections were tried in several other localities, discontinuance being due partly to difficulty of making suitable arrangements for dependable daily catches and partly to rapid accumulation of material from preferred localities. None of these short series showed any significant tendency to departure from the general pattern of annual and seasonal distribution observed at the two standard stations.

Offshore Abundance of Dinoflagellates

In a period of more than twenty years, by cruises, expeditions, and special trips, at hundreds of stations, more than five thousand catches of phytoplankton have been taken off shore at distances ranging from a mile or two to mid-ocean. Up to 1938 most of these catches were obtained from surface levels by Scripps Institution boats, ships of the U.S. Navy, ships of the U.S. Coast and Geodetic Survey, patrol boats of the Mexican Government, boats of the International Fisheries Commission and of the California Fish and Game Commission, coastwise passenger steamers, private yachts, and commercial fishing boats. Although most of the collecting was done in California waters, some hundreds of catches were made in localities ranging from Peru to Alaska, Alaska to Hawaii, and San Francisco to Australia. In and after 1938 most catches were made below the surface, six in addition to the surface at levels successively ten meters deeper. All were obtained by the Scripps Institution research ship "E. W. Scripps," using the Allen closing bottle of five liters capacity at all levels.

Dinoflagellates were obtained at nearly all offshore stations but the numbers were usually small, or even negligible. Out of the thousands of catches only about five hundred showed numbers as large as one thousand cells per liter. Many of these were at distances of five or ten miles from shore but less than fifty were more than thirty miles from shore. None were as much as one hundred miles from shore. Apparently, dinoflagellates thrive best in localities fairly near shore, at least so far as waters of the eastern North Pacific Ocean are concerned. This tendency to lower abundance far offshore in Pacific waters is shown also by the fact that no catch as large as 25,000 cells per liter was taken as far as twenty miles from shore. Even in the Gulf of California only one station showed as many as 100,000 cells per liter as far as thirty miles from shore. Apparently, the "red water" abundance of more than a million cells per liter, sometimes observed at piers or near shore, occurs only rarely, or never, at distances more than twenty miles to seaward.

Depth Distribution

Because less than one thousand catches were taken at any particular level below the surface in the boat collections of the twenty year period, and because the time and locality relationships of these catches at any particular level were not demonstrably identical, or even completely comparable, no conclusive generalizations are warranted by the evidence. On the other hand, this evidence seems to present reasonably dependable support for some provisional suggestions.

Although not entirely convincing, available evidence suggests rather strongly that the surface level (above five meters) is usually representative of conditions at boat stations even when the greatest single catch is made at some other level. Aside from the possibility that the ten meter level tends to show *extreme* abundance a little more often it appears probable that the surface level leads in *significant* numbers of armored dinoflagellates more often than any number. However that may be, it is clear from the data that large abundance, or locally superior abundance, is rarely found at or below thirty meters. Even in the Gulf of California, highest abundance at a strongly productive station (1939, Sta. 48, 163,000 cells per liter) has been found as low as thirty meters in only one instance and the next to highest abundance (Sta. 51, 209,000) at that level in one other instance.

No such relationships have been observed in the open sea off the California coast where most of the collecting beneath the surface has been done. That is to say, really significant numbers of armored dinoflagellates have not been observed below thirty meters and very few locally superior numbers at or below that level. Tendency to decline of production below thirty meters is shown also by the occurrence of catches equalling or exceeding 1,000 cells per liter. Of such, eighteen were found at thirty meters, twelve at forty, nine at fifty meters and three at sixty meters.

Locality Distribution

Although differences between certain inshore stations and between inshore and offshore stations in respect to productivity have been mentioned in preceding pages it seems desirable to emphasize the irregularities of distribution as revealed by use of sea going vessels. Even the crude collecting by tow nets used for phytoplankton in 1917 and 1918 showed clearly that catches from different stations off shore were not alike in the numbers of organisms obtained. For example, no two of the eighteen stations sampled in the Institution cruise in the Gulf of Santa Catalina in 1917 were alike in the numbers of dinoflagellates caught. Indeed the numbers of species represented were different at most of them (Allen 1921a, Table I). The hundreds of stations sampled since that time by the more accurate methods of the Allen Filtration Net and the Allen Closing Bottle have yielded evidence substantially similar to this. Therefore, it seems to be reasonable to conclude that localities offshore tend to differ among themselves in the numbers present at any particular time and that those showing significant numbers differ in total numbers produced in a particular season or year. The evidence is not so strong for dinoflagellates as it is for diatoms (on account of smaller numbers) but it points to the same conclusion.

Especially interesting items concerning differences between offshore stations were obtained from stations 1 and 2 (respectively ten and five miles offshore from the Scripps Institution) which were sampled frequently in the years 1921, 1922, 1923, 1924, 1926, and 1927. Series of catches at a number of depths were taken at these two stations on the same days, usually within a very few hours of each other, thus making the catches as nearly comparable as is possible by use of only one boat. Except in the series when catches at both stations were too small to have numerical significance the numbers found at one were never the same as those found at the other. On thirty-two days of collecting in 1921, Station 2 gave some evidence of more production of dinoflagellates, numbers above 300 cells per liter being found on ten days as compared with four days at Station 1. However, Station 1 yielded over 2,000 cells per liter on June 22 when less than 300 were taken at Station 2, thus indicating that while a few samples may show differences between stations they do not necessarily reveal the extent or the characteristics of the differences. In 1922, Station 1 was more nearly like Station 2 in the number of significant catches (19 to 23) but it was far inferior in the size of catches. Through the shorter period of sampling in 1923 the two stations were not strikingly different, although there appeared to be a slight reversal in favor of Station 1. Through the longer period from mid-May to late August in 1924 there was a definite showing of better production at Station 2 (Sleggs 1927). After the Kofoid Closing Bottle was displaced by the lighter Allen Closing Bottle in 1926 collecting was done much more quickly and effectively and comparisons of abundance at the two stations became even more dependable than they had been formerly. Again production of dinoflagellates appeared definitely superior at Station 2 although the numbers of diatoms were smaller there throughout the series. An offshore cruise in August showed the numbers of dinoflagellates to be practically negligible from one end of the Gulf of Santa Catalina to the other in all stations to seaward, much too small for trustworthy comparison of production at different stations. Results of collections in 1927 emphasized those for 1926, Station 2 (five miles) showing larger abundances than Station 1, (ten miles) regularly throughout the summer series. Thus the evidence from off shore appears to be equally convincing with that from inshore in support of the idea that abundances of dinoflagellates are generally unlike at different stations.

Indeed, there is strong indication that stations differ in annual totals of production. While for the dinoflagellates there is a suggestion that the more prominent differences in annual production may be related to distances from shore of the stations sampled, it remains reasonably certain that locality differences are observable between stations far off shore and that those differences have little, if any relation to linear distances from shore.

Taxonomic Limitations

At first thought, it might be supposed that twenty years of acquaintance with dinoflagellate populations represented in series of collections widely ranging in the Pacific Ocean would result in the accumulation of a long list of names of component species. On the other hand, it does not require much experience to show that accurate naming of new species or invariably accurate determination of most species is impossible if progress is to be made in quantitative studies of general populations in Nature. Consequently, with few exceptions, the names appearing in the phytoplankton records of the Scripps Institutions are tentative approximations intended to suggest the ranges of variety in the populations or to facilitate the tracing of distinguishable forms through times and spaces. Sometimes, also, names of doubtful appropriateness were recorded in order to have a guide to particular material in case opportunity appeared or necessity arose for critical treatment. Under such limitations the following incomplete and largely suggestive list of eleven genera and forty-one species has been assembled. It is quite reasonable to suppose that many other genera and at least three times as many species were actually represented in the more than twenty thousand samples of phytoplankton examined microscopically.

Dinoflagellates Listed at Scripps Institution

(Naming according to Schiller 1933)

- *Ceratium*
  - *arietinum* Cl.
  - *azoricum* Cl.
  - *candelabrum* (Ehr.) Stein
  - *contortum* (Gour.) Cl.
  - *extensum* (Gour.) Cl.
  - *furca* (Ehr.) Clap. et Lach.
  - *fusus* (Ehr.) Duj.
  - *Kofoidii* Jörg.
  - *lineatum* (Ehr.) Cl.
  - *longipes* (Bail.) Gran
  - *longirostrum* Gour.
  - *macroceros* (Ehr.) Cl.
  - *pentagonum* Gour.
  - *pulchellum* B. Schr.
  - spp.
  - *trichoceros* (Ehr.) Kof.
  - *tripos* (O. F. Müller) Nitzsch
- *Dinophysis*
  - *acuminata* Clap. et Lach.
  - *acuta* Ehr.
  - *arctica* Meresch.
  - *caudata* Sav-Kent.
  - *ellipsoides* Kof.
  - *hastata* Stein
  - spp.
- *Goniaulax*
  - *catenella* Wh. and Kof.
  - *polyedra* Stein
  - spp.
- *Gymnodinium*
  - spp.
- *Noctiluca*
  - *miliaris* Sur.
- *Oxytoxum*
  - spp.
- *Peridinium*
  - *crassipes* Kof.
  - *depressum* Bail.
  - *divergens* Ehr.
  - *globulus* Stein

- *granii* Ostf.
- *minutum* Kof.
- *oceanicum* Vanhöffen
- *pentagonum* Gran
- *pyriforme* Pauls.
- spp.
- *steinii* Jörg.

Phalacroma
- *rudgei* Mur. and Wiht.

Podolampas
- *bipes* Stein

Prorocentrum
- *dentatum* Stein
- *micans* Ehr.

Pyrocystis
- *lunula* Schütt

So far as the records for twenty years are concerned only seven species representing four genera ever reached large abundance or a commanding lead in production. These include one species of *Goniaulax* (*G. catenella* Whedon and Kofoid) and the only recorded species of *Noctiluca* (*N. miliaris* Suriray), which were prominent only in the Gulf of California. *Ceratium fusus* (Ehr) Duj. was never dominant in leadership even at greatest abundance and *Goniaulax polyedra* Stein was excessively abundant only in 1939, one year in twenty. For most of the twenty years the totals of dinoflagellate production were mainly dependent upon three species i. e. *Ceratium furca* (Ehr) Clap et Lach, *Ceratium tripos* (O. F. Müller) Nitzsch, and *Prorocentrum micans* Ehr. Of the three the latter was much the most prominent in spite of its great inferiority in size. Other species encountered with frequencies sufficient to keep them well in mind as components of the dinoflagellate populations were: *Ceratium azoricum* Cleve, *C. candelabrum* (Ehr) Stein, *C. Kofoidii* Jörg., *C. macroceros* (Ehr) Cleve, *C. pentagonum* Gour., *C. tripos* (O. F. Müller) Nitzsch, *Dinophysis acuminata* Clap. et Lach., *D. caudata* Sav.-Kent, *D. ellipsoides* Kof., *Gymnodinium* spp., *Noctiluca miliaris* Sur., *Oxytoxum* spp., *Peridinium crassipes* Kof., *P. depressum* Bail., *P. divergens* Ehr, *P. Granii* Ostf., *P. oceanicum* Vanhöffen, and *P. Steinii* Jörg.

Outstanding Species

One unexpected result of the twenty years of daily observations at La Jolla and Pt. Hueneme piers was the finding that only four species of dinoflagellates could be rated as outstanding for the period as a whole. In order of perennial prominence these were *Prorocentrum micans* Ehr,, *Ceratium furca* (Ehr.) Clap. et Lach., *C. tripos* (O. F. Müller) Nitzsch, and *Goniaulax polyedra* Stein, but only the first and last named ever became so excessively abundant as to be primarily responsible for extensively conspicuous occurrences of "red water." Under the obligatory conditions of enumeration the identity of all of these species was often uncertain, especially when the numbers were small or the characteristics highly variable.

PROROCENTRUM MICANS Ehr. Although it was the smallest of the four conspicuous species, *Prorocentrum micans* Ehr. (Fig. 3) rarely caused definite uncertainty as to identification except for the occasional presence of a still smaller form about half as large as the one most common. The smaller specimens were never very numerous and they were included in the records with the others.

P. micans Ehr. was represented in La Jolla Bay in every year of the twenty but not at Pt. Hueneme in 1935, and the total numbers for the year were extremely low in 1925, 1926, 1928 and 1931. The extreme height of total annual production was reached in La Jolla Bay in 1939 (Fig. 7) with other notably productive years in 1924, 1930, 1933, 1936, 1938, 1939, (Fig. 7) in three of which (1924, 1933, and 1939) the showing of high production was due largely to single cases of "red water." At Pt. Hueneme only the years 1920 and 1922 produced totals large enough to attract particular attention and at no time in the twenty years was "red water" recorded there. The annual pattern of production, as determined by adding numbers for all of the twenty years for successive periods of four weeks (Fig. 8), was very much like that for total dinoflagellates, as might be expected because of the high prominence of this species in dinoflagellate populations. According to this pattern the summer season is most favorable in most years.

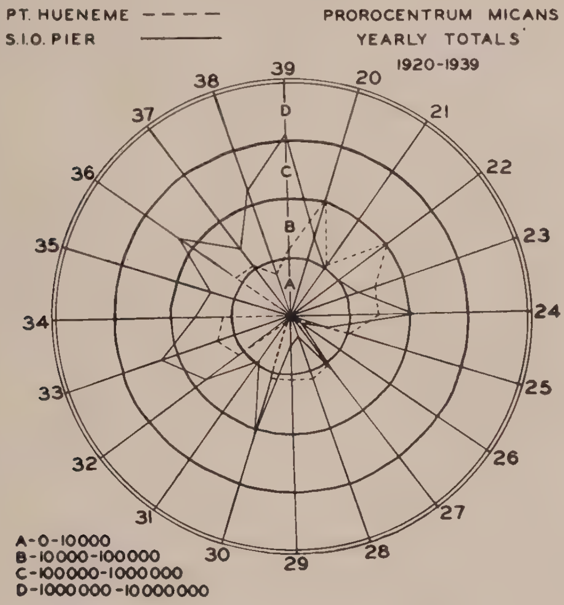

Fig. 7. Total numbers per liter of daily catches of *Prorocentrum micans* for each of twenty years; to show fluctuations of abundance by year periods, also larger numbers at La Jolla after changing methods.

The relationship of *P. micans* Ehr. to evidence of ten year periodicity for dinoflagellate annual totals requires attention. Even more striking than for all dinoflagellates combined is the preponderance of this species at La Jolla in the second ten years, as compared with the first ten. But, this showing corresponds exactly with the change to the settling method of collecting at La Jolla. A suspicion that this condition invalidates the evidence offered in preceding pages as indicating five, ten, or twenty year periodicities arises necessarily. How-

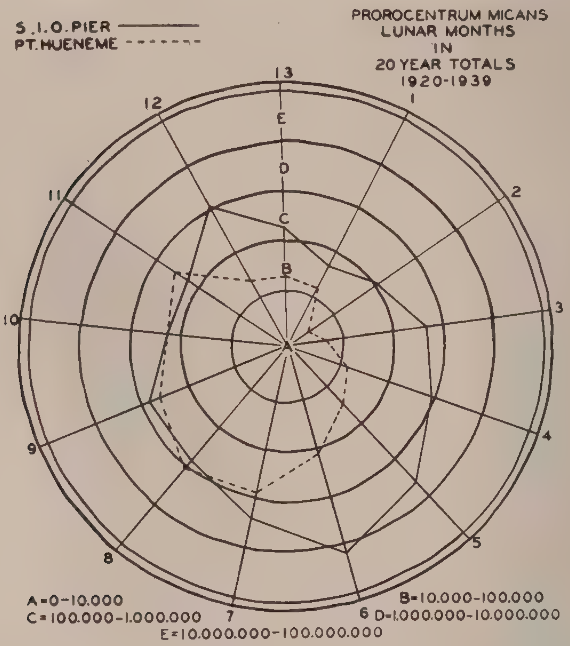

Fig. 8. Twenty years totals of numbers for each four week period ("lunar month") of annual thirteen; to show higher abundance in summer in year pattern of *Prorocentrum.*

ever, it should be remembered that *P. micans* Ehr. is strongly adhesive and cohesive and that the loss through a filtration net is much less when numbers are very large. Therefore, the representation in catches of more productive years might have been expected to be more nearly complete than in less productive years even if filtration collecting had been continued. That is to say, it still remains probable that the difference between the two ten year periods was real although less extreme than indicated by the records. Also the decline in the second five years occurred before methods of collecting were changed, thus indicating some tendency to periodic fluctuation. In addition, catches of larger forms of dinoflagellates showed increase in the second ten years and it is not certain that *P. micans* Ehr. carried enough influence to invalidate the evidence for greater production in the second ten years. Furthermore, it should be remembered that temperatures (p. 25) appeared to be more favorable for total dinoflagellates for the second ten years. Still, there is room for reasonable doubt for total dinoflagellates as well as for this particular species, if one prefers to entertain it. Exhaustive analyses of existing data might solve the problem but that is impossible at present.

Aside from problems of its periodicity and relative abundances, *P. micans* is interesting because it is the only armored dinoflagellate which has been shown to be extensively used as food by California sea mussels (Fox 1936). It is mentioned by Lebour (1925) and by Schiller (1933) as a source of food for mussels, oysters, and other shell fish. Lebour also says that pilchards and other fishes feed upon it extensively. If it has recognizable value as food for these groups of sedentary and natant animals it may be supposed to have similar value as food for other groups, perhaps many of them. Especially is it natural to suspect that numerous kinds of plankton animals feed upon it.

Ceratium furca (Ehr.) Clap. et Lach. *Ceratium furca* ranked second in constancy of representation along shore, especially at the Scripps Institution pier. Not only was it found in many single catches in every year of the twenty but it was recorded in at least eleven out of thirteen four week periods in nineteen out of twenty years at La Jolla Bay. Only in 1931 did the representation occur in as few as six months (four early and two late in the year). Although the largest catches were obtained usually in the late Spring (Fig. 9)

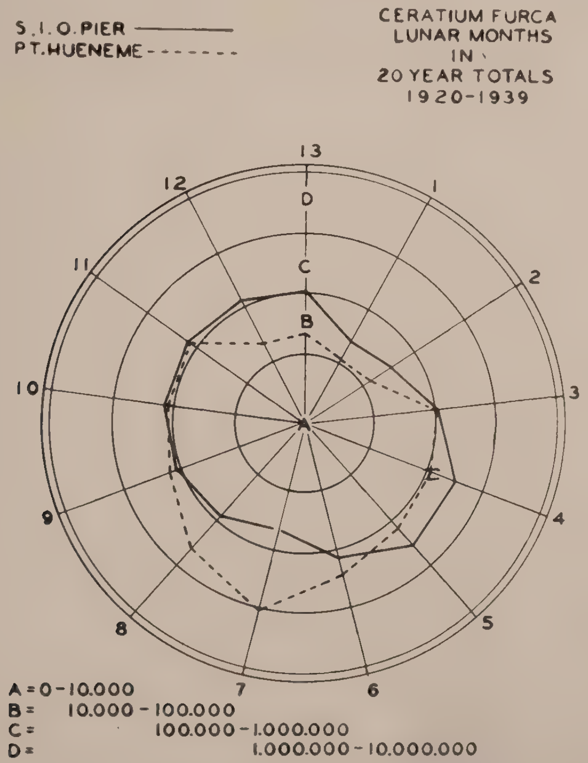

Fig. 9. Twenty years totals of numbers of *Ceratium furca* for each four week period of annual thirteen; to show higher abundance in Spring at La Jolla and Summer at Pt. Hueneme in year pattern.

abundances almost as large were found in other seasons in certain years. At Pt. Hueneme few catches (none large) were made in either of the first two months or the last two months in most years. On the other hand, there were only ten four-week periods (scattered through the aggregate two hundred and sixty) in which none were recorded, no single year in which representation so nearly failed as at La Jolla in 1931. The annual pattern of occurrence showed largest abundance a little later than at La Jolla (Fig. 9). Total numbers for twenty years were nearly fifty percent larger at Pt. Hueneme than at La Jolla.

In the thousands of catches from widely different localities, it is probable that ninety-five percent of the specimens conformed fairly closely to the diagrammatic sketch shown in Fig. 3. There could be no doubt of their close relationship to the species even if some may have been separable from it by more or less nearly exhaustive study.

CERATIUM TRIPOS (O. F. Müller) Nitzsch. *Ceratium tripos* (Fig. 3) ranked third in constancy of representation at both stations. Only in 1931 was it absent from the records in more four-week periods than it was present. Numbers were small (most often, none) in January and December of most years. Indeed, there were few years in which the abundances were more than negligible in the first and last weeks at La Jolla and the first and last twelve weeks at Pt. Hueneme. Stated in another way, there was a distinct tendency toward better production in the period from mid-April to mid-October at La Jolla and from mid-May to mid-October at Pt. Hueneme. Strangely enough, in view of the shorter period, the latter station showed a total production for the twenty years which was more than twice as large as that for the other. The annual pattern (Fig. 10) shows definitely not only the winter thinness of populations and the summer high productiveness but it shows the later period of production at Pt. Hueneme. Apparently, this species, more than any other of the four, tends to conform to seasonal periodicities and to their modification by latitudinal influences.

Identification of *C. tripos* was often highly unsatisfactory. Not only is this species extremely variable but so are a number of close allies. Nevertheless, it seems reasonable to assume that more than half of the identifications were correct and that the others were close enough for general purposes. Certainly most of the specimens observed conformed fairly well to the diagrammatic outline in Fig. 3. This is the largest species of the leading four (Fig. 3) and it might be expected to contribute notably to the food supply of small animals, but the Scripps Institution has not obtained any evidence to support that expectation and the literature contributes none.

GONIAULAX POLYEDRA Stein. *Goniaulax polyedra* (Fig. 3) is only a little larger than *Prorocentrum micans* Ehr., with which it shares the primary responsibility for occurrences of "red water" along the California coasts. Unlike the latter, or either of the two *Ceratiums, G. polyedra* is decidedly erratic in occurrences, missing any recording throughout whole years at both stations, notably 1923, 1927, 1931, 1936, and 1939. In several other years the occurrences were very few or the numbers very low. The showing for high abundances was still worse. Only at La Jolla was conspicuous abundance reached and there only in 1932 and 1938. At Pt. Hueneme, 1926 and 1937 were the only years in which total numbers for a four-week period exceeded 100,000 cells per liter. Indeed, the rank among the leaders depends mainly on the prominent "red water" at La Jolla Bay and off San Diego in June 1939, although production was very high in the La Jolla locality in October and November 1932. Because of the erratic occurrence and rarity of excessive production it is necessary to view the graphic representation of the year pattern (Fig. 11) with considerable caution. The indication of summer increase at La Jolla (even the late summer increase at Pt. Hueneme) corresponds moderately well with tendencies shown by the other leading species but the high productivity indicated for three four-week periods late in the year at La Jolla is surprising. However, reference to manuscript tabulations proves this to be mainly dependent on 1932, with recognizable trends in that direction in five other years, trends somewhat more definite at Pt. Hueneme. Evidently, the twenty-year period is too short to establish conclusively a year

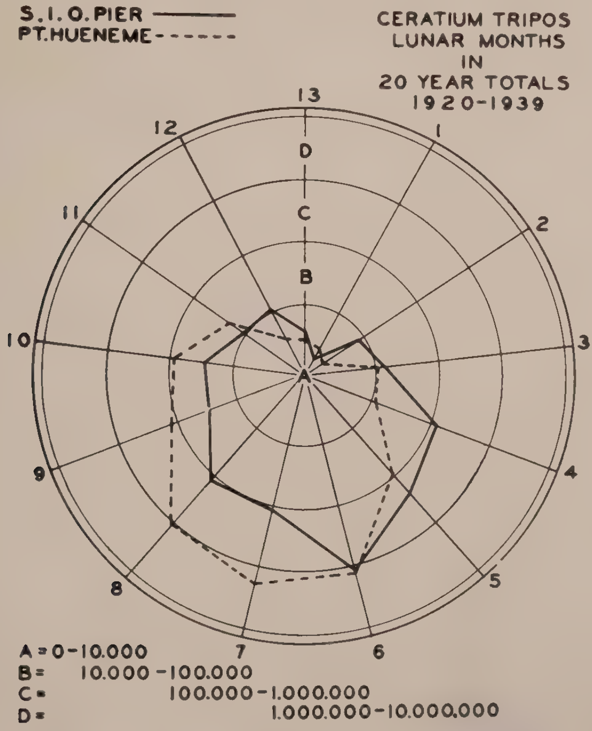

Fig. 10. *Ceratium tripos.* Twenty year totals of numbers for each four week period of annual thirteen; to show strong preference for warmer seasons in year pattern.

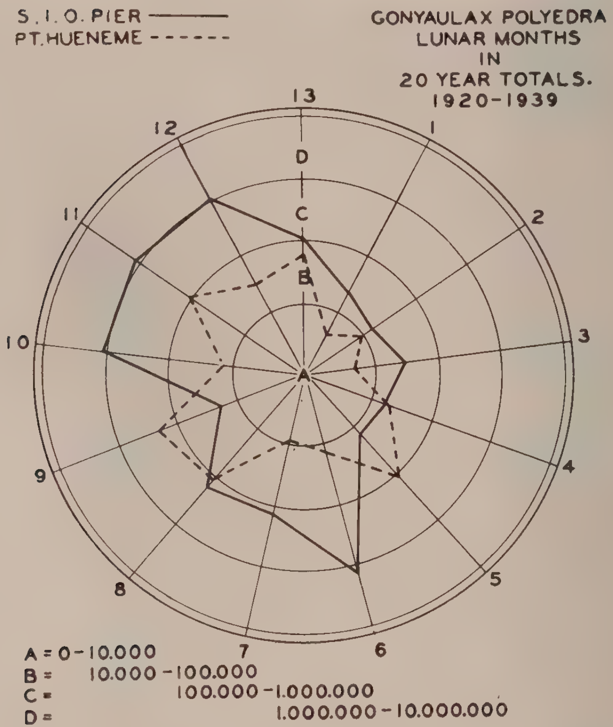

Fig. 11. *Goniaulax polyedra.* Twenty year totals of numbers for each four week period of annual thirteen; to show peculiar year pattern of a species occurring erratically.

pattern for a species so erratic in occurrence as *G. polyedra.* On the other hand, the tendencies seem definite enough to warrant expectation that this pattern will be approached more often than any other in future years.

Like the two *Ceratiums, G. polyedra* has not yielded evidence of importance as a contributor to the fundamental food supply of the sea. Nevertheless, a number of records indicate an important relationship to animals at certain times and under particular conditions. Because of the reports by Torrey (1902) and others, this species has acquired a bad reputation for injury to marine animals, including fishes, when it appears in such abundance as to cause "red water." The absence of recognizable lethal effects on animal populations in and near La Jolla Bay in "red water" of 1939 suggests that mere occurrence of that phenomena is not sufficient to cause widespread destruction of marine animals. Apparently, there must be contributing causes to accompany it in producing lethal effects. However, it should be remembered that Sommer, Whedon, Kofoid, and Stohler (1937) have identified a closely allied species of *Goniaulax* (i. e. *G. catenella* Whedon and Kofoid) as a cause of "mussel poisoning." Perhaps no *Goniaulax* is harmful to man or to marine animals ordinarily, but only under specific conditions. Still, possibilities of injury are little less interesting than probabilities. Therefore, *Goniaulax* is likely to hold a prominent place because of its evil reputation.

Identification of *G. polyedra* was rarely positive although usually probable. The small size impaired observation of essential details and the rounded form was responsible for confusing differences of positions of specimens on the slide. In addition, there was enough of resemblance to allied species and to *Goniodoma polyedricum* (Pouchet) Jörgensen to cause more or less confusion in certain cases. On the other hand, so many specimens appeared to be recognizable that the percentage of error must have been small. The diagrammatic sketch in Fig. 3 indicates the general appearance of Scripps Institution specimens.

Summary

1. Hundreds of catches from widely different localities and regions in the Pacific Ocean show definitely that dinoflagellates may be found almost anywhere, and thousands of catches taken daily at limited numbers of stations over periods of five to twenty years show just as definitely that the numbers are rarely very large, mostly below thousands per liter in most localities.

2. At the two standard stations, La Jolla and Pt. Hueneme, only four species of armored dinoflagellates attained outstanding prominence. Of these, only *Prorocentrum micans* Ehr. and *Goniaulax polyedra* Stein ever became so excessively abundant as to cause "red water": *Ceratium furca* (Ehr.) Clap. et Lach. and *C. tripos* (O. F. Müller) Nitzsch were prominent because of constancy of representation in at least moderate numbers.

3. Daily observations in La Jolla Bay over a period of twenty years gave ample opportunity to note the streakiness and patchiness of surface distribution of dinoflagellates, *Prorocentrum* in particular, its streakiness often showing on the surface where it was easily visible.

4. Some thousands of catches obtained by systematic cruising at sea by the Scripps Institution have shown that large production of armored dinoflagellates is confined almost entirely to levels above thirty meters depth and to a zone within twenty-five miles of shore. So far, no "red water" has been observed as far off shore as thirty miles in Southern California waters.

5. The daily catches at the two standard stations have yielded evidence suggesting five or ten year periodicities in productivity. They show also fairly good conformity to a year pattern of summer increase and winter decrease in production.

6. The Scripps Institution's adaptation of the measured water method has proven to be highly satisfactory in collecting armored dinoflagellates, *a closing bottle being used for sampling when working from a boat offshore.*

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